# Chapter 3
# Ice Control

## 3-1. Introduction

*a. Purpose.* The practice of ice control is aimed at influencing or modifying the behavior of ice in the annual cycle of ice formation, growth, and decay. For example, ice control may be employed to promote ice cover formation or stabilization at a time much earlier than it would occur under normal conditions. In other words, ice control can lead to the formation of a stationary ice cover where the natural ice condition at a given time in the winter may be open water and the continuous production of frazil ice, causing freezeup ice jams downstream. In some cases, it is possible to control the timing and location of ice breakup. Some forms of ice control are used to prevent ice formation or limit ice thickness, with resulting benefits for navigation, for structures subjected to ice forces, or for downstream areas liable to breakup ice jams.

*b. Approach.* Ice control is divided into two broad areas: mechanical control and thermal control.

(1) Mechanical control focuses on ice retention: creating a stationary ice cover or retaining moving ice in a chosen location. Most of these techniques are intended to influence the beginning of the ice-formation–growth–decay cycle, but a few are designed to address the ending portions of this cycle. Most mechanical ice control is achieved by flexible, often seasonally deployed, structures, such as ice booms, or by rigid (or semirigid) structures, such as weirs, artificial islands, piers, groins, cribs, or dolphins (Tuthill 1995). An ice boom is a barrier made from floating pontoons or timbers anchored by chain and wire rope. Booms are used to initiate an ice cover, thereby minimizing frazil ice generation. Booms also benefit navigation and hydropower production by retaining ice later in the winter and early spring. Examples of rigid structures are the ice piers that have been constructed on the Ohio River above Cincinnati. These are simply large bridge piers or cells placed fairly close together to slow, stop, or redirect ice flow. A tow may take shelter below these piers during an ice run. In general for navigable waterways, mechanical ice control measures need to permit the continuance of navigation during winter (Perham 1988a). For example, navigable ice booms provide an open section to allow vessel passage. Most major inland rivers have a 2.7-meter (9-foot) navigation depth and handle barge traffic. Harbors and fleeting areas on most of these navigable rivers are present in almost any type of river reach, including the inside and outside of bends, at confluences, and in straight reaches. Structural ice control measures would most likely have to be located outside of the harbors and fleeting areas to permit free access of barge tows to moorings and wharfs and to accommodate cross-stream traffic (Perham 1988b).

(2) Thermal control is employed to maintain open water where ice covers would normally occur, or to at least limit the thicknesses of ice that normally would grow. Air bubblers, for example, are used to bring up warmer water from some depth to melt ice or at least retard its growth. Waste heat, introduced to a river, harbor, or lake from thermal power plants or industrial processes, is also an effective means of thermal control. (An offshoot of air bubblers is a high-flow air system, which releases large quantities of air at some depth to induce diverging horizontal water velocities at the surface. These surface currents prevent ice or debris from passing or they deflect ice or debris away from critical areas. These systems are discussed in Part III, Chapter 19.)

*Section I*
*Mechanical Ice Control*

### 3-2. Ice Control Using Flexible Structures

Ice booms are the most widely used type of flexible sheet ice retention structure. The first such structures were long booms of logs chained or wired end to end into a long line across a water body. The logs provided flotation as well as structural strength. Sometimes, several logs were bolted side by side to obtain sufficient flotation. The booms were anchored onshore and to boom docks (rock-filled timber cribs) in midstream. The trash booms used at hydroelectric plants to keep floating debris from power canals are similar and may have been the first to use a continuous wire rope for structural strength. The most common type of ice boom consists of large floating timbers held in place by a wire rope structure and buried anchors (Figure 3-1). The weight of the wire rope structure and junction plates is carried by supplemental floats. Ice booms have been installed primarily by hydroelectric power companies to minimize the volume of ice impinging on their trash racks, to minimize the formation of frazil ice, and to keep head losses to a minimum. The boom or series of booms collects floating ice and accelerates the formation of an ice cover upstream. When the discharge is controlled, as at a power station, a decrease in flow will further accelerate ice cover formation. Booms have been installed to restrain and thereby minimize the ice contribution to ice jams or ice pileups on shore that can block water intakes. Booms assist navigation by holding brash ice and floes in place so that they do not flow downstream and block narrow channels. Booms are not intended to restrain ice at breakup, but under quiescent hydraulic conditions they may serve this purpose.

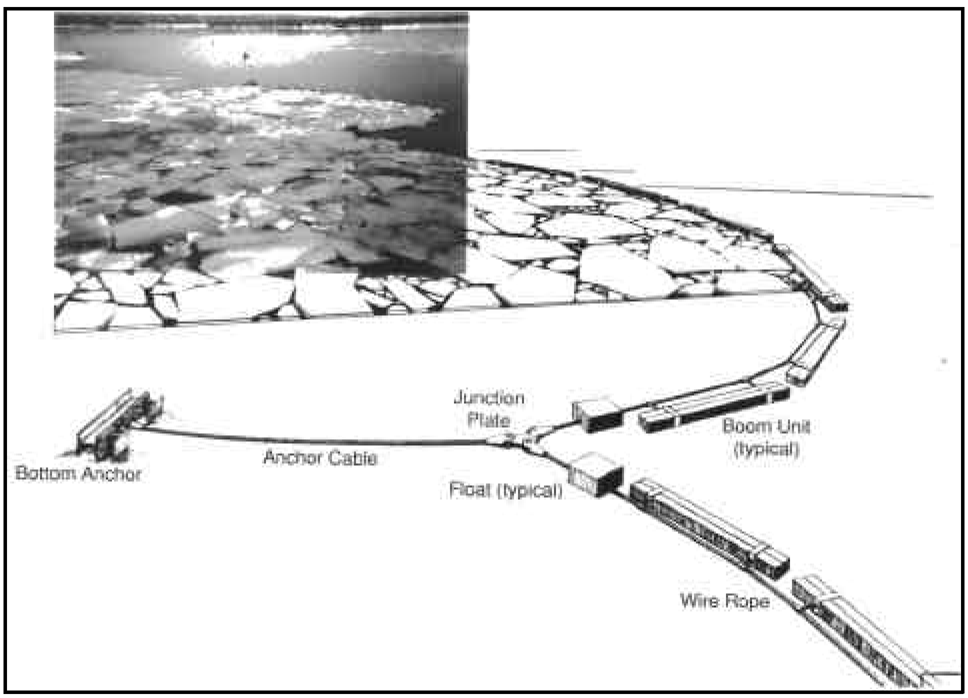



**Figure 3-1. Typical ice boom arrangement.**

*a. Features of flexible structures.* Flexible cable or wire rope structures are used to hold floating ice booms in place. The structures themselves are compliant but strong, and their ability to stretch or flex in response to the impact of moving ice sheets has prevented failure. They are used on generally accessible bodies of water where one must control ice in winter while permitting unrestricted water use during the warm months. The ice cover that they help form and stabilize protects water intakes and navigation channels against excessive ice encroachment. The most important advantages of flexible structures are:

- The main structural components usually have a negligible effect on water flows.

- The structures (except for buried anchors) are readily installed prior to the ice season and removed afterward.

- The structures can withstand the passing of ice breakups.

- A variety of standardized components are available for a wide range of loads.

- The structures can be worked on using common maritime equipment, such as barges, cranes, winches, and tugs.

A list of flexible structures is given in Table 3-1.

*b. Boom configuration.* As shown in Figure 3-2, booms have been built in many configurations: some crossing the entire width, some with a gap to permit navigation, some restraining ice on only one side of the channel, and some more or less in the middle of a lake with open passage around both ends. The boom units are chained to wire rope boom cables, which connect to the shores or to midchannel anchor cables, usually at 30- to 122-meter (100- to 400-foot intervals), depending on the load. Until recently, the most common type of boom section was a 0.3- × 0.6- × 6-meter (1- × 2- × 20-foot) timber. The use of steel boom units of rectangular or circular cross section is gaining acceptance owing to reduced maintenance costs and improved performance compared to traditional timber booms.

*c. Function*. Boom structures can be installed across a portion of a river or across the entire width, according to the amount of control needed. The floating timbers intercept moving ice floes, frazil slush, and brash ice to form an unconsolidated ice cover upstream of the boom. Within 10 days the ice cover usually consolidates by the ice pieces freezing together. To be effective, an ice boom must restrain an ice cover at the surface without restricting water flow, and it must move up and down with the ice cover. An unconsolidated ice cover develops most rapidly when the water velocity (bringing ice floes to the boom) is as large as possible without causing appreciable quantities of ice to pass beneath the boom. Field tests showed that this velocity for a straight, 2.7-meter-deep (9-foot-deep) channel was 0.46 m/s (1.5 ft/s). This value is also optimum for the deeper but somewhat irregular Beauharnois Canal (located in Canada); the smooth ice cover that develops there allows efficient power generation in winter. In several major installations the mean velocities vary from 0.29 to 0.84 m/s (0.95 to 2.75 ft/s).

*d. Site considerations.* Locations where ice booms have been used successfully share common characteristics. The discharge is fairly constant and there are no abrupt changes in cross-sectional area. A boom can be used in fairly deep water, anywhere from 3 to 18 meters (10 to 60 feet) or more. Successful booms require a stable river bottom, i.e., one unaltered by sediment transport. If water velocities are too high, the ice floes can be drawn under the boom. A location that sustains a natural ice cover, even if only occasionally, is generally feasible. Accepted design criteria to achieve good boom performance are a Froude number, based on flow depth, no greater than 0.08, and a surface velocity no greater than 0.69 m/s (2.25 ft/s). Higher values indicate that ice thickening conditions may be present or that upstream progression of a retained ice accumulation may not be possible. At some sites, physical or numerical modeling may be necessary to select the optimum location.

## Table 3-1. Flexible Ice Control Structures

| Type of Structure | Figure No. | General Function* | Water Body | Material | Dimensions (m) | Span (m) | Force Level† (kN/m) | Water Depth (m) | Avg. Water Velocity (m/s) | Organization | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Ice Booms** | | | | | | | | | | | |
| Single timber | | icfs, p | St. Lawrence River | Douglas fir | 0.36×0.55×9 | 122 | 8.5[m] | 5–15 | 0.3–0.8 | Ontario Hydro, Cornwall & Toronto Ontario; PASNY, Massena, New York | |
| | 3-3c | icfs, p | Lake Erie | Douglas fir | 0.36×0.55×9 | 122 | 20[d] | 5.5 | 0.45 | Ontario Hydro, Niagara Falls, Ontario; PASNY, Niagara Falls, New York | |
| | 3-3c | icfs, n | Lake St. Peter | Douglas fir | 0.36×0.55×9 | 122 | 9.3[m] | 3 | 0.3 | Transport Canada, Marine Services, Montreal | |
| | 3-1 | icfs, n | St. Marys R. | Douglas fir | 0.3×0.6×6 | 62.5 | 10.6[m] | 3–10 | 0.8 | Detroit District, U.S. Army Corps of Engineers | 76-m-wide opening between boom ends for ship navigation |
| Double timber | 3-3f | icfs, n, p<br>icfs, ijr | Lake St. Francis<br>Oil Creek | Douglas fir & steel<br>Douglas fir & steel | 0.36×0.55×9<br>0.83×0.83×20; 0.67×0.67×16 | 122<br>38 | Unknown<br>6.7[m] | 8<br>0.6 | 0.75<br>0.50 | Hydro Quebec, Montreal<br>CRREL and Oil City, Pennsylvania | |
| Single pontoon | 3-3a | icfs, ijr | Des Prairies R. | Hollow steel | 0.4×0.8×6 | 68.5 | 44[e] | 4.5 | 0.5–0.85 | Hydro Quebec, Montreal | |
| | 3-3a, 3-5 | icfs, n, p | Lake St. Francis | Hollow steel | 0.4×0.8×6 | 61 | 16[d] | 6 | 0.43 | Seaway Transport Canada, St. Lambert, Quebec | |
| | 3-6 | icfs | Allegheny R. | Steel; filled with foam | 0.4×0.8×6 | 76 | 16.4[d] | 1.6 | 0.35 | Pittsburgh District, U.S. Army Corps of Engineers | |
| Double pontoon | 3-3g | icfs, n, p | Beauharnois Canal | Hollow steel pontoon; steel frame | 0.9 (diam.) ×6; parallel pontoons, 1.8 on center | 36 | 46.7[m] | 10.4 | 0.73 | Hydro Quebec, Montreal | Maximum ice force measured |
| Single timber (direct load)<br>Rope | <br>3-3e | icfs, t, p<br>icfs, x | St. Marys R.<br>St. Lawrence R. | Timbers<br>Nylon & polypropylene braided rope | Miscellaneous<br>0.18 (diam.) ×91 | 21.3<br>81 | Unknown<br>Unknown | 3.4<br>6.7 | 0.58<br>0.6–0.75 1.2–1.8 | Edison Sault Electric Co., Sault Ste. Marie, Michigan<br>St. Lawrence Ship Channel Division Ministry of Transport, St. Lambert, Quebec | Timbers connected end to end |
| Plastic pipe | 3-3d<br>3-16 | icfs, p | Pasvik R. | Plastic pipe; steel wire rope | 0.3 (diam.) | Unknown | Unknown | Unknown | Unknown | Power Plant, Hestefoss, Norway | |
| **Shear booms** | 3-3i | t, d | Missouri R. | Steel pipe; wood planks | 1.1–1.35 (diam.) ×24 | 122 | Unknown | ~9 | 71.8 | Montana Power Co., Great Falls, Montana | |
| | 3-3h | t, d | New Clayton Lake | Steel pipes; wood planks | 0.33–0.5 (diam.) ×7.3 | 216 | Unknown | 36.5 | Unknown | Appalachian Electric Power Co. Clayton Development, Virginia | |
| **Scow boom and weir** | | icfs | St. Lawrence R. | Scow; stone weir | 1.4 (avg scow depth); 2.5 (height of weir) | ~238 | Unknown | ~3.6 | 3–4.5 | | Boom can pass ice during high flows |
| **Timber boom and weir** | | icfs | Chaudiere R. | Wood timbers; steel cable; concrete pier | 1.5 (height of weir) 1.2 (height of boom) | 42.9 | 14.6[d] | ≤3.5 | ≤2.6 | Quebec Ministry of Natural Resources | |
| **Frazil collector lines** | 3-8 | icfs, x | Ottauquechee R. | Braided nylon line | 15 (lengths of lines); 0.15 (spacing between lines); 98% open | 5 | 0.005–0.008[s] | 0.3–0.5 | 0.7–1.1 | CRREL | 0.1-m spacing recommended |
| **Fence boom** | 3-10<br>3-11 | icfs, ijr, x | Mascoma R. | Wood 2 × 4s; wire rope | 1.2 (height); 0.1 (gaps); 70% open | 16.5 | 11.7[d] | 0.4–0.5 | 0.43 | CRREL | |

*icfs = ice cover formation and stabilization
d = shear or diversion
t = trash collection or diversion
ijr = ice jam reduction

x = experimental
p = hydroelectric power
n = navigation

†m = measured
d = design criterion
e = estimated from damage
s = shear drag coefficient
kips = kilo pounds of force

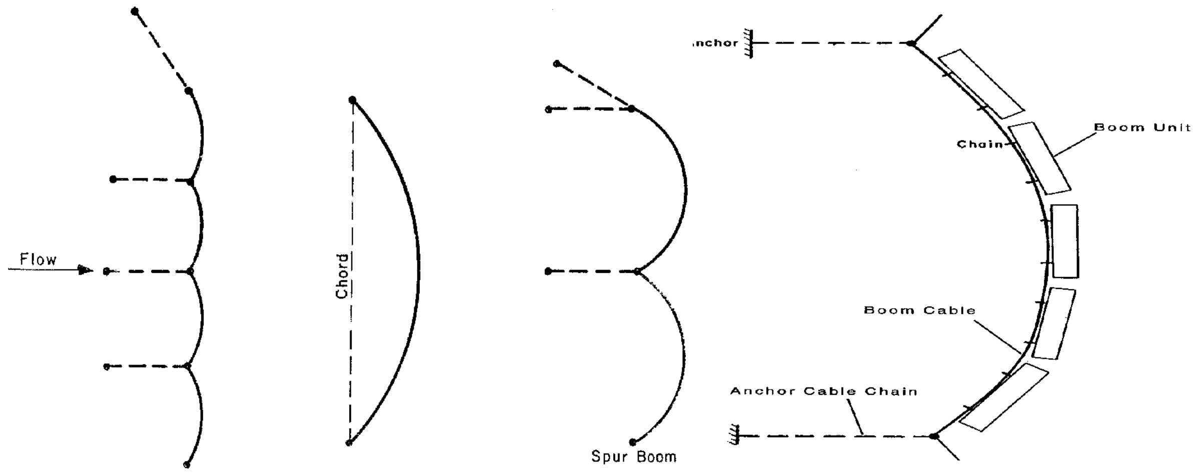



**Figure 3-2. Ice boom configurations**

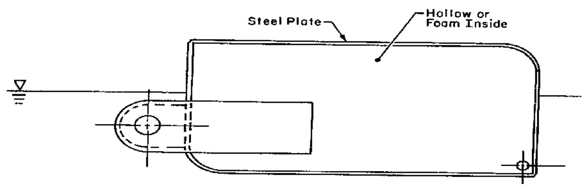
*e. Boom components.* Although ice booms vary in function and appearance, their wire rope structures are similar. The boom cables are longer than the spacing between the anchors, giving each boom span a sag configuration. In existing structures, boom cable length exceeds the span length by values ranging from 6 to 25 percent, corresponding to *sag ratios* (maximum offset of cable from the span divided by the span length) of 0.15 to 0.30. The greater the cable length is, the lower the tension in the cable is, but sag ratios in excess of about 0.20 excessively increase material quantities and cost.

(1) Individual wire ropes are connected by steel junction plates that are supported by buoys or floats. Galvanized wire ropes are often used for longer life, although the strength of the galvanized wire is 10 percent less than that of uncoated wire when new.

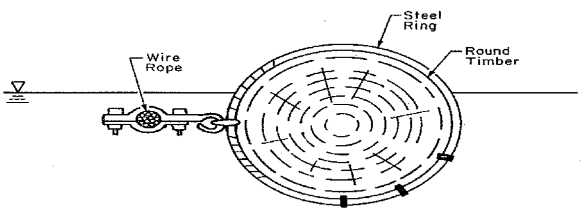
(2) Figure 3-3 shows a variety of ice boom designs. Designs h, i, and k have been used as shear booms for waterborne trash and logs; the floating material is expected to slide along the upstream face of the boom. The proper combination of buoyancy and stability can be determined through tests and analysis. Wooden timbers can lose effectiveness by becoming waterlogged, another factor prompting the current transition to steel boom units.

(3) Anchor types for ice booms vary, depending on the type of riverbed and bank materials. Depending on width, a structure that reaches from shore to shore will have anchors onshore and midstream anchors along the river bottom. Midstream anchor lines from the river bottom to the floating parts are generally about 12 times longer than the water depth. Typical anchors are shown in Figure 3-4. The cell structure is sometimes used at the midstream end of a spur boom, which reaches only part way across a river.

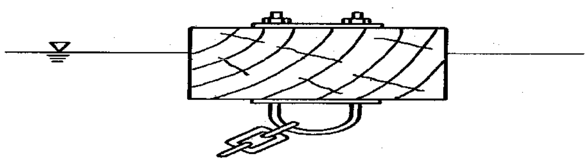
*f. Examples of flexible booms (Perham 1983).* An example of river ice control using an ice boom is found on the St. Marys River at Sault Ste. Marie, Michigan. Soo Harbor covers a large area, and immediately downstream from the harbor is a 183-meter-wide (600-foot-wide) man-made navigation channel called Little Rapids Cut. Below the cut lies Lake Nicolet, with its low velocity flows. The channel is dredged to a minimum depth of 8.2 meters (27 feet), and ocean-going vessels and lake carriers of various sizes up to 1000 feet (305 meters) long use it. Ice broken from Soo Harbor by passing ships would accumulate in Little Rapids Cut, so much so that at times the river discharge was retarded and



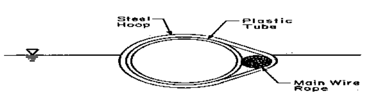

a. Rectangular pontoon boom



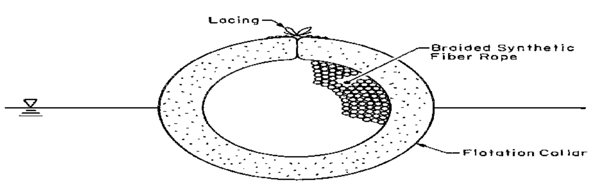

b. Round timber boom



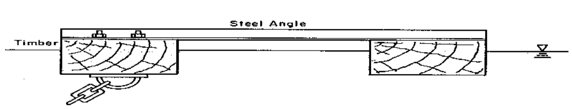
c. Single rectangular timber boom



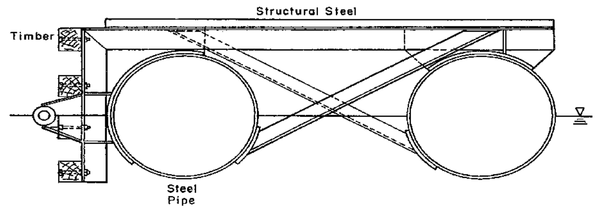

d. Plastic tube boom



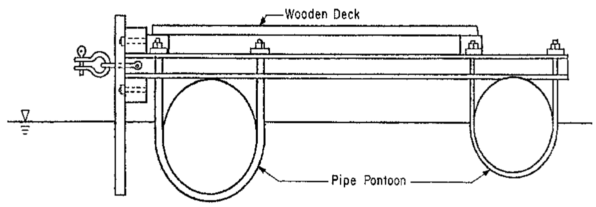

e. Synthetic fiber rope boom



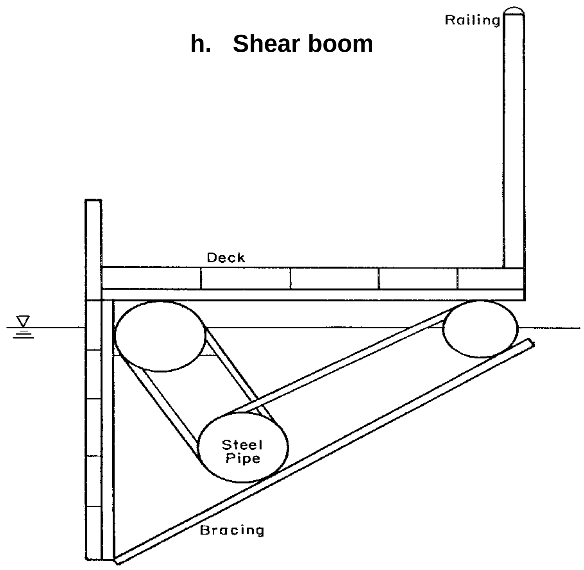

f. Double rectangular timber boom



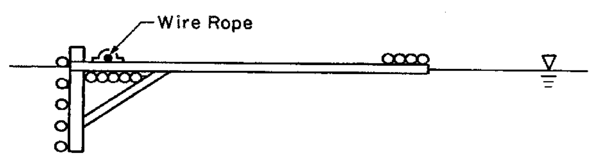

g. Double steel pontoon boom



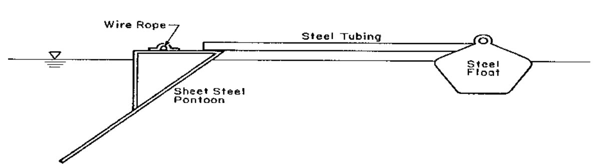

h. Shear boom



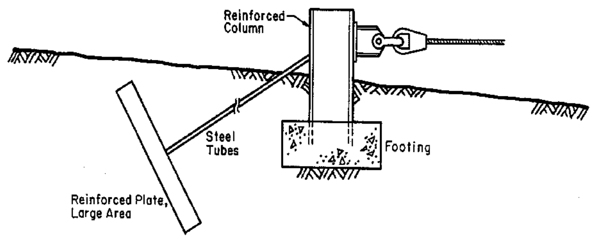

i. Shear boom



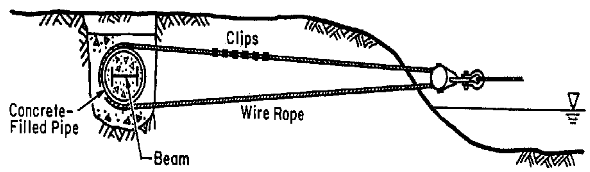

j. Wooden pole boom



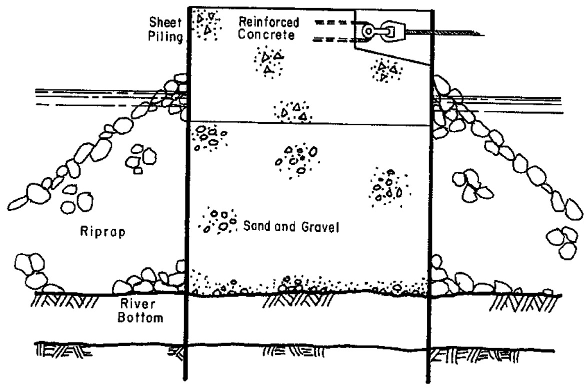

k. Triangular-skirted pontoon boom



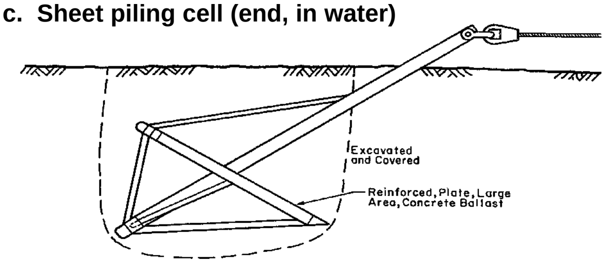

a. Deadman and pedestal (end, land)



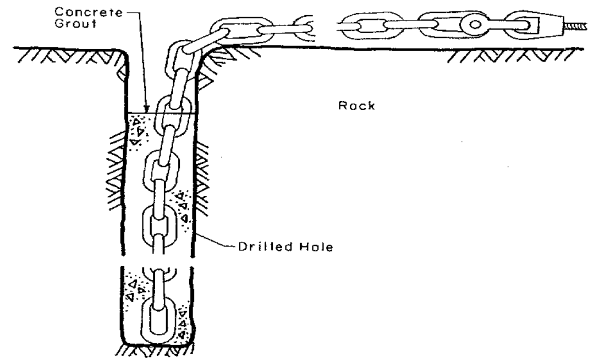

b. Deadman and wire rope (end, land)



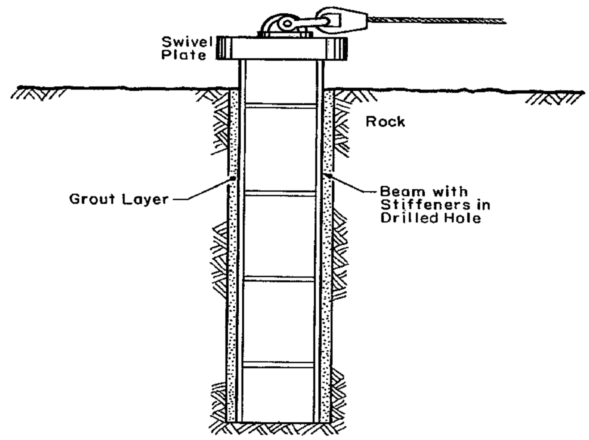

c. Sheet piling cell (end, in water)



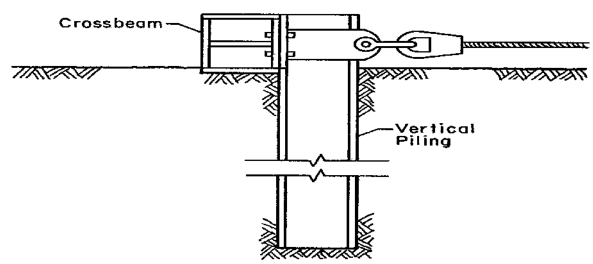

d. Steel anchor (endpoint in water)




e. Grouted chain (midpoint, in water)




f. Grouted weldment (midpoint, in water)




g. Piling and crossbeam (end, midpoint, land, in water); two or more are needed

**Figure 3-3. Cross sections of ice boom timbers and pontoons for a variety of ice boom designs**

**Figure 3-4. Typical ice boom anchors**

unacceptably high water levels would develop in the harbor. Also ferry traffic to an island community was frequently disrupted.

(1) An ice–hydraulic–navigation model study of Soo Harbor and Little Rapids Cut determined the optimum location, orientation, and size for a floating ice boom. A boom with a 76-meter-wide (250-foot-wide) navigation opening was designed, built, and installed in 1975 at the upstream end of Little Rapids Cut. Later, two gravity structures (see paragraph 3-3*c*) were placed upstream of the boom to inhibit some troublesome lateral movement of the ice sheet along the western shore. The booms and the structures were

removed in the spring and reinstalled in the fall. Artificial islands eventually replaced the gravity structures (see paragraph 3-3*d*). This work was done as part of a now-completed demonstration program; the booms continue to be used because they provide stability to the ice cover during storms and intermittent ship transits, and they minimize ice interference with the ferry (Perham 1985).

(2) One of the largest booms to be installed in recent times (1981) is 2380 meters (7800 feet) long and located in Lake St. Francis upstream of the Beauharnois Canal in Canada (Figure 3-5). It was designed to accommodate ship navigation and was extensively tested as a model. The Lake Erie–Niagara River boom, although older, is 2680 meters (8800 feet long).

(3) A boom of similar construction was built in 1982 on the Allegheny River upstream of its confluence with Oil Creek at Oil City, Pennsylvania (Figure 3-6). Oil City has a long history of ice jams and floods that were caused by large deposits of frazil ice downstream of the confluence in a deep section of the river. The accumulations especially restrict flows from ice breakup on Oil Creek, which precedes ice breakup on the Allegheny River. The ice cover upstream of the boom typically stabilizes in early winter, reducing the frazil ice supply to the freezeup jam below the Oil Creek confluence.

(4) The 2680-meter-long (8800-foot-long) Lake Erie–Niagara River ice boom, located at the head of the Niagara River at the east end of Lake Erie, promotes ice arching and decreases the frequency and severity of lake ice runs into the Upper Niagara River. Retention of Lake Erie ice reduces the frequency of ice jams and ice blockages of hydroelectric intakes upstream of Niagara Falls. In 1997, the original timber pontoons were replaced with steel pipe boom units. This change is expected to increase the ice retention capacity of the boom and reduce maintenance costs.

*g. Boom design considerations.* There are a number of loads and other actions that must be considered when designing an ice boom (Foltyn and Tuthill 1996). Fluctuations in water level may allow the boom to pound on the bottom if it is too close to shore. Because of the resulting damage, this should be avoided. Generally, the amount of ice that will bleed through a small gap between the end of the boom and shore is negligible. The total force on the ice boom is

$$F_i = f_w \pm f_a + f_g + f_p + f_k - f_s \pm f_v \tag{3-1}$$

where

$f_w$ = water drag force on ice cover

$f_a$ = wind drag force on ice cover

$f_g$ = gravity force

$f_p$ = water flow pressure at beginning of ice cover

$f_k$ = impact forces from collecting ice floes

$f_s$ = shear force between ice and shore

$f_v$ = forces resulting from vessel–ice–structure interaction.

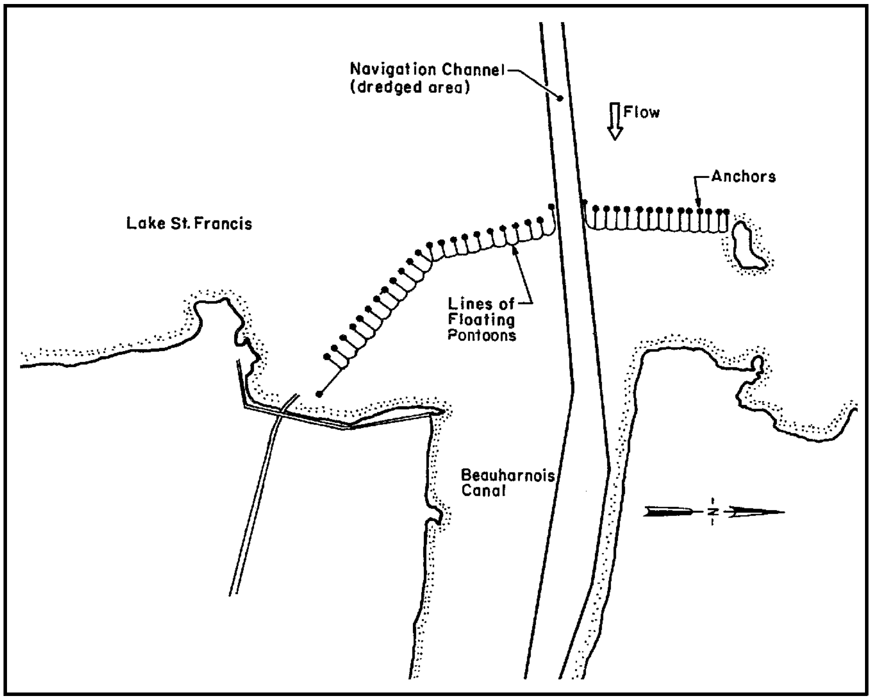



**Figure 3-5. Plan view of the Lake St. Francis ice boom built in 1981**

Most of these are self-explanatory or will be explained more fully in the example problem. The shear force between the ice and shore $f_s$ is currently indeterminate, but field observations have shown that ice loads attributable to an unconsolidated ice cover come from the area upstream of the boom that measures four or five times the river width in length. In other words the drag forces on the ice cover in excess of four or five *B* (the river width) are taken by the shore and are not felt by the boom. Boom unit stability should be considered, as well as the maximum ice restraint capacity of the boom unit.

(1) The restraint characteristics of a generally applicable timber configuration are given in Figure 3-7. The timber has a no-load submergence of 0.75 and a connection point upstream on the bottom. The curves show that the ice restraint force will be about the same for anchors pulling horizontally and anchors pulling downward at a small angle $\alpha = \tan^{-1} 0.08$ until the tilt $\beta$ of the timber is about 35 degrees. At 35 degrees, the $\alpha = 0$ curve changes slope rapidly and diverges from the $\alpha = \tan^{-1} 0.08$ curve. The physical problem here is that, as the tilt angle nears 40 to 45 degrees, the ice can slide over the timber; this tends to make this portion of the curves unreliable. The restraint capacity of a boom timber increases by the cube of the timber width.

(2) The override effect can be and is used for rectangular boom-unit cross section as a protective measure that helps the boom survive the high loads imposed at breakup. Generally, the rectangular-section timber booms have a load capacity ranging from 74 kg/m (50 lb/ft) to 298 kg/m (200 lb/ft), depending upon boom design and ice type. There are double pontoons that have load capacity of over 744 kg/m (500 lb/ft) for rectangular boom-unit sections. The overtopping resistance of the 0.76-meter-diameter (2.5-foot-diameter) circular-section boom units on Lake Erie is approximately 1120 kg/m (750 lb/ft), four times greater than the maximum ice resistance of the original timber boom units. The load capacity depends on the buoyancy, the righting couple or moment, and the anchor location.

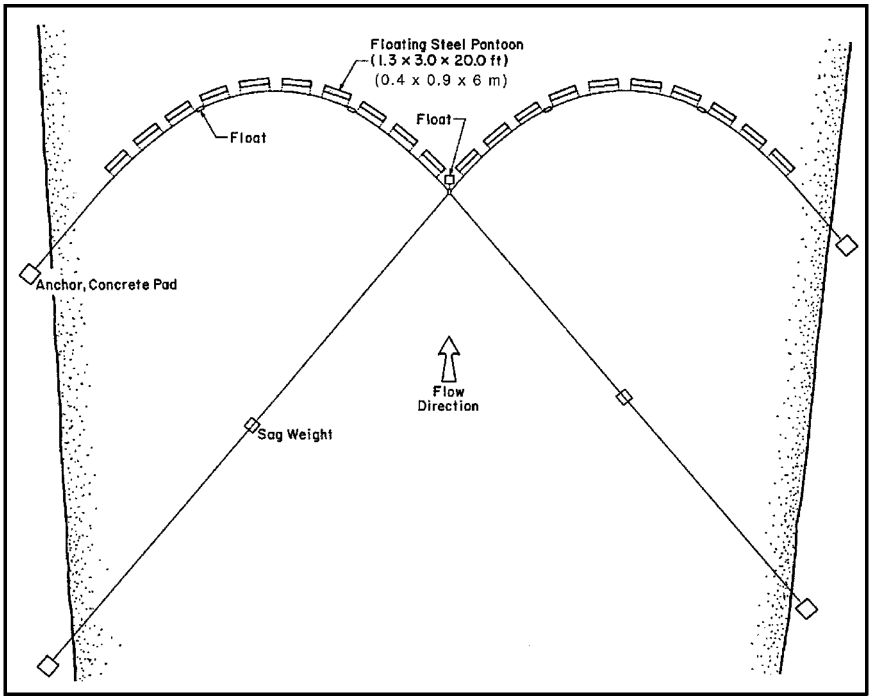



**Figure 3-6. Plan view of the Allegheny River ice boom built in 1982**

(3) A failure analysis should be made of the multicomponent structure to estimate the increased loads exerted on members adjacent to a component that fails. The structure also should be evaluated for its response to a solid ice sheet that only acts at one or two locations along the boom, and to an ice sheet that starts moving while frozen to the floating timbers. The calculated forces in these cases could be extremely high. Under such circumstances the load increase may not be distributed uniformly to the anchor points.

*h. Example problem of ice boom design.* This example is based on a power canal 3.2 kilometers (2 miles long) and 3.0 meters (10 feet) deep with a 7.6-centimeter-thick (0.25-foot-thick) ice cover. It is 54.9 meters (180 feet) wide at the bottom and 61.0 meters (200 feet) wide on the top. The hydraulic slope with an ice cover is $3.81 \times 10^{-4}$. The canal is essentially straight and aligned with the prevailing winds which can reach 27.7 m/s (91 ft/s) at 9.1 meters (30 feet) above the surface. The bottom has a Manning's roughness coefficient of 0.032 and a Froude number of 0.11, which is higher than desired. The initial ice cover roughness coefficient is 0.05. The composite roughness coefficient is 0.041, determined using Equation 4-2. Equation 3-1 above has a number of unknowns to be determined:

$$f_w = \gamma_w R_i S (5B) \tag{3-2}$$

where

$\gamma_w$ = specific weight of water = 62.4 lb/ft$^3$ (1000 kg/m$^3$)

$R_i$ = hydraulic radius influenced by the ice, assumed at 5 feet (1.5 meters)

$S$ = uniform flow slope

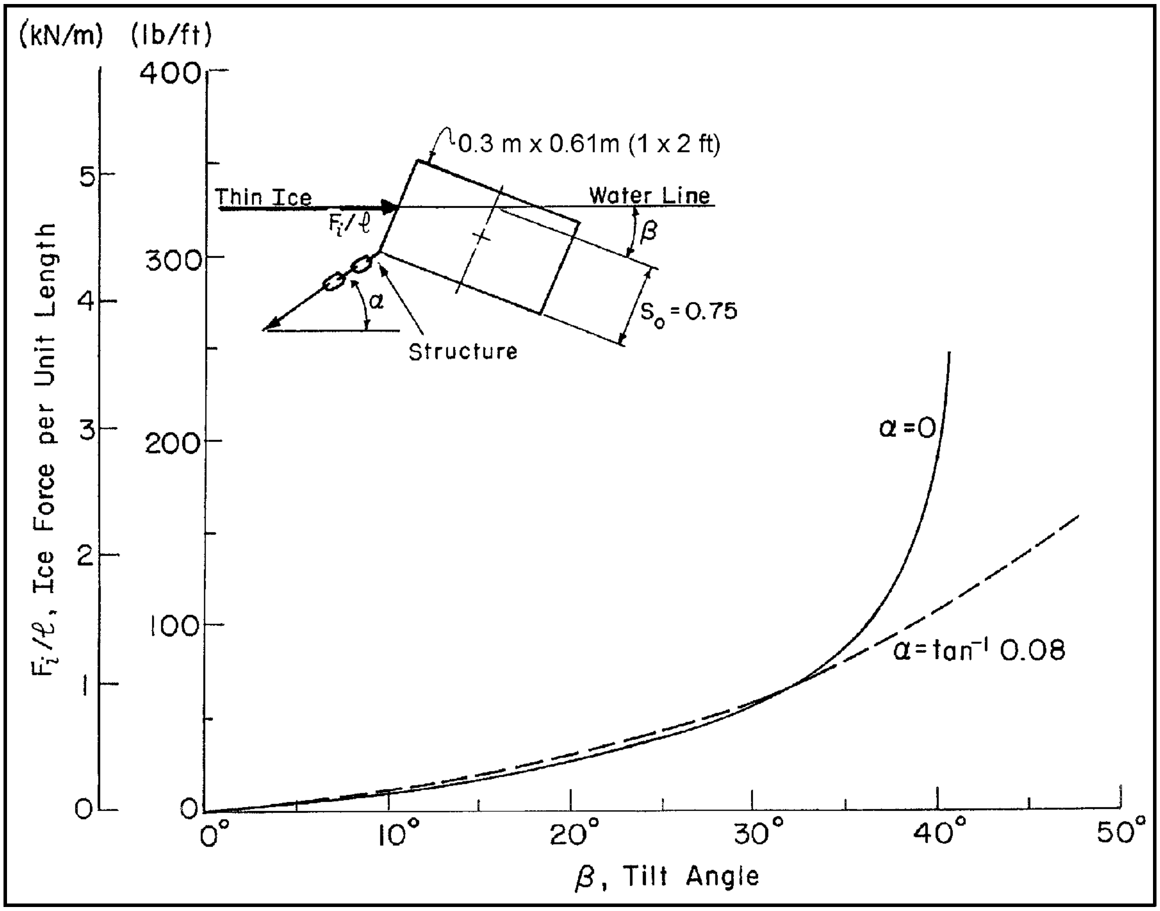



**Figure 3-7. Ice restraint for a 0.3- × 6.1-meter (1- × 20-foot) boom timber for the conditions indicated**

$B$ = channel width

$f_w = 62.4 \times 5 \times 3.81 \times 10^{-4} \times 5 \times 200 = 119$ lb/ft (177 kg/m)

$$f_a = c\,\rho_a\,U^2\,5B \tag{3-3}$$

where

$c$ = drag coefficient, which can vary between $1.7 \times 10^{-3}$ and $2.2 \times 10^{-3}$

$\rho_a$ = air density, kg/m$^3$ (lb/ft$^3$)

$U$ = mean wind speed at the 30-foot (9.1-meter) height, ft/s (m/s)

$f_a = 2.2 \times 10^{-3} \times 0.00257 \times (91)^2 \times 5 \times 200 = 70$ kg/m (47 lb/ft)

$$f_g = \gamma_i\ 5B\,h\,S \tag{3-4}$$

where

$\gamma_i$ = specific weight of ice = 918 kg/m$^3$ (57.3 lb/ft$^3$)

$h$ = ice thickness = 0.076 meters (0.25 feet)

$f_g$ = 57.3 × 5 × 200 × 0.25 × 3.81 × 10$^{-4}$ = 8.2 kg/m (5.5 lb/ft).

The values of $f_p$ and $f_k$ are considered negligible. The value of $f_s$ is taken into account by using 5$B$ and $f_v$ is not considered in this case. So, repeating Equation 3-1,

$$F_i = f_w \pm f_a + f_g + f_p + f_k - f_s \pm f_v$$

$F_i$ = 119 + 47 + 5.5 + 0 + 0 – 0 ± 0 = 255.7 kg/m 171.5 lb/ft.

That is 255.7 kilogram-force per lineal meter (171.5 pounds-force per lineal foot) of boom, assuming the wind is blowing downstream. For calculating the tension in the boom cables, see Foltyn and Tuthill (1996).

*i. Other flexible structures*. Two other types of flexible structures may be described, frazil collector lines and fence booms. Both of these concepts were examined experimentally in the 1970s and early 1980s, but only the fence booms have received additional study and development in more recent years. Similar in concept to frazil collector lines, frazil nets have been used to promote ice cover formation upstream of hydroelectric dams in Sweden.

(1) Frazil collector lines, or line arrays, are made from nylon, polypropylene, polyester, or wire rope. An array is anchored in a stream, and active frazil ice freezes to each line (Figure 3-8a). Overnight accumulations 10 to 13 centimeters (4 to 5 inches) in diameter on each line are common. As the lines and frazil ice float on the stream's surface, the entrapped interstitial water is practically stationary and freezes quickly to form an ice cover over the entire line array (Figure 3-8b); even 0.64- and 0.79-centimeter-diameter (1/4- and 5/16-inch-diameter) wire ropes are buoyed up by the frazil ice accumulations. In concept, covering a troublesome open-water reach of a canal or stream with one or several sets of steel or synthetic fiber lines seems feasible. The ideal combination of unit length and frequency of units needed to prohibit further supercooling was never determined. If the lines are naturally buoyant, an array can be anchored where it will freeze into the ice sheet without being buoyed by frazil ice; it would then become a reinforcement and a means for supplemental restraint. Arrays of buoyant lines could also be used to stabilize existing large ice sheets by holding them in place against flow forces after they crack free from shore. The idea would be for the lines to expand the area that a buoy, or a timber, might be expected to reliably influence. An example is shown in Figure 3-9. Such cracks can result from water level changes, ship passages, or warm water discharges. Also, several sets, probably without the shore anchors shown in Figure 3-9, have the potential for delaying spring ice movement on a section of river. The loss of a line array during ice breakup would be a possibility, and the consequences of this loss must be considered.

(2) A fence boom is a structure supported across a stream by steel cables and resting on the streambed (Figure 3-10). The fence boom has little effect on streamflow before icing conditions start. Its appearance is that of a slatted snow fence or a wooden grate. It is stable when connected to single anchor points buried in each bank because of the curved shape it takes in response to the hydrodynamic and static water pressures acting on it. Active frazil ice generated in the stream attaches to the vertical

**a. Array of lines, 4.9 × 15.2 meters (16 × 50 feet)**

**b. Resulting ice cover**

**Figure 3-8. Frazil collector lines**

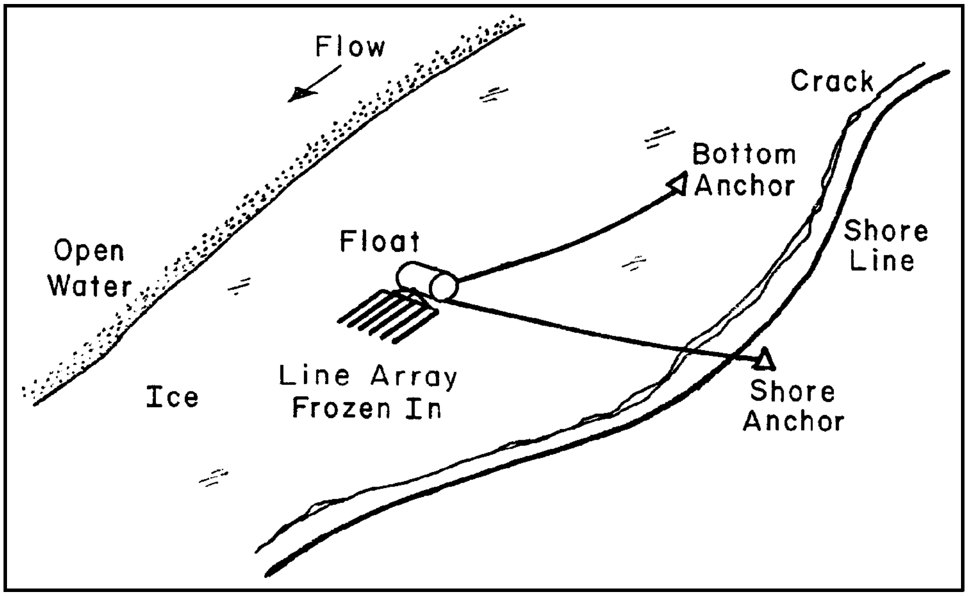



**Figure 3-9. Line array anchoring an ice sheet that has cracked free from shore**

**Figure 3-10. Fence boom, 1.2 meters (4 feet) high, across the Mascoma River, New Hampshire**

bars and eventually fills in the spaces between the bars from the streambed to the surface. Water flows continuously, so the frazil ice blockage causes the water level upstream of the boom to rise and overflow the blockage. This, in turn, increases the elevation of the region that can be blocked by frazil ice. Eventually, a pool is created upstream, with water flowing over the top of the fence boom (Figure 3-11). An ice cover develops and progresses upstream until a surface flow velocity of 0.69 m/s (2.25 ft/s) is reached. Field tests of the original fence boom were successful, but it was tested in only one small river.

**Figure 3-11. Pool formed by the action of frazil ice on a fence boom**

Streambed erosion was a problem, pointing to the need for bed protection. A similar free-standing fence boom is used to form an ice cover upstream of a small hydropower project in northern Japan.

## 3-3. Ice Control by Rigid or Semirigid Structures

Rigid or semirigid structures may or may not have moving parts. They are appreciably more rigid than a typical ice boom, but their deflection in response to the horizontal push of an ice sheet is on the same order as the deflections that develop in the ice sheet itself. Because these structures are generally unyielding, they are particularly susceptible to ice sheet impact and thermal expansion loads. The state of the art in design today is generally based on the conservative values of load and stress developed for dams and bridges. A list of rigid or semirigid structures is given in Table 3-2.

*a. Pier-mounted booms.* Boom elements attached to piers may be either movable (e.g., the Montreal ice-control structure) or fixed (e.g., the spillway barrier at the Sigalda Project in Iceland).

(1) The Montreal ice-control structure (Figure 3-12) was built primarily to compensate for the ice conditions caused by the narrowing of the St. Lawrence River because of construction of the Expo ‘67 World’s Fair. The structure, which is permanent, originally used floating steel booms or stop logs set between concrete piers to collect ice floes and help stabilize an ice cover earlier in winter than would normally be the case. The booms were designed to move vertically in guide slots in the piers, kept ice-free by radiant electric heat. The 2.04-kilometer-long (1.27-mile-long) structure cost approximately $18 million in 1964–65. The operating levels for the booms were determined by model studies and analysis of the backwater effects from the formation of the ice cover downstream in Montreal Harbor and below. At these levels the large quantities of ice expected from the Lachine Rapids upstream can be stored beneath the ice cover. The structure was designed using dam technology to provide high structural integrity. The booms were designed to float, but they were not allowed to turn over as they might do with a flexible rope structure. In spite of their strength, they were susceptible to damage by the concentrated impact loads of moving ice sheets. Also, the operation of the structure has been affected by

**Table 3-2. Rigid or Semirigid Ice Control Structures.**

| Type of Structure | Figure No. | General Function* | Water Body | Material | Dimensions (m) | Force Level† (kN/m) | Water Depth (m) | Avg. Water Velocity (m/s) | Organization | Notes |
|---|---|---|---|---|---|---|---|---|---|---|
| **Booms** | | | | | | | | | | |
| Floating (pier-mounted) | 3-12 | icfs, ijr | St. Lawrence River | Steel pontoons; concrete piers | 1.7 × 1.8 × 25 (pontoons) | $73^d$ (pontoons) 146 (piers) | 6.7 | ≤1.8 | Canadian Coast Guard, Ministry of Transport, Montreal | A few pontoons were broken by ice impact |
| Fixed | 3-13 | icr | Tungnaa R. | Reinforced concrete | 5.5 (height w/flash boards ) 2.5 × 110 | $146^d$ 3000 centerload | 6–6.4 | ≤4.9 | Landsvirkjun (National Power Co.), Reykjavik, Iceland | Reservoir overflow spillway |
| | 3-14 | ir, d | Tungnaa R. | Reinforced concrete | 7.9 × 6.1 × 60 | $58^d$ | 7–9 | Unknown | Landsvirkjun (National Power Co.), Reykjavik, Iceland | Power canal inlet |
| **Border ice bridge** | | icfs | Dvina R. | Ice | ≤200 | Unknown | deep | quiet | — | Reinforced with wire at times |
| Artificial islands | | | | | | | | | | |
| Low | 3-19b | icfs, n | St. Lawrence R.; Lake St. Peter | Stone; glacial till (0.6 - 1 m diam) | 10.4 (diam. at water line); ~79 (diam. at base); 2.5 (height above LWL) | Unknown | 2.7–5.2 | 0.3–0.5 | Canadian Coast Guard, Ministry of Transport, Ottawa | |
| High | 3-19a | icfs, n | St. Lawrence R.; Lake St. Peter | Stone; glacial till | 10.9 (diam. at water line); ~74 (diam. at base); 4.3 (height above LWL) | Unknown | 6.4–7.5 | 0.3–0.5 | Canadian Coast Guard, Ministry of Transport, Ottawa | |
| | 3-20 | icfs, n | St. Lawrence R.; Lake St. Louis | Quarry stone; armor stone | Square: 11.9 (length of side at water line); 35 (length of side at base); 5.8 (height) | Unknown | 4.4 | Unknown | Seaway Transport Canada, Cornwall, Ontario | Undergoing evaluation |
| **Light tower bases** | 3-22 | icfs, n | St. Lawrence R. | Timber cribs & piles | Square: 7.6 (length of side) | $1500^d$ | 1.8 | Unknown | Canadian Coast Guard, Ministry of Transport, Ottawa | Replacement for failed structure |
| | 3-29 | icfs, n | Lake St. Peter | Concrete & steel piles | Conical: 2.4 (diam. at top ); 45° incline | $830–1040^d$ | 2.0 | 0.3–0.5 | Canadian Coast Guard, Ministry of Transport, Ottawa | No failure |
| | 3-30 | n | Lake St. Clair | Steel shell & piles; concrete cap | 5.5 (diam. at top); 11 (diam. at base) | $790^d$ | 5.5 | ~0 | U.S. Coast Guard, Cleveland Ohio | |
| | 3-31 | n | Lake Erie | Steel | Square: 0.37 (length of side) | $2800^d$ with 1.67 m ice | 3.0 | ~0 | U.S. Coast Guard, Cleveland, Ohio | |
| **Groins** | 3-16 | icfs, p | Pasvik R. | Stone | Unknown | Unknown | Unknown | Unknown | Water Resources & Electricity Board, Oslo, Norway | |
| | 3-15 | icfs, p | Burntwood R. | Stone; earth | 9 (max.ht.); 274 (length); 0.9–1.2 (diam. of nose armor boulders) | Unknown | 7 | ≤5.8 | Manitoba Hydro, Winnipeg | Flow increased by river diversion; ice boom also used |
| **Timber cribs** | 3-21 | icr | Narraguagus R. | Timbers; stone | 4.3 (length) × 2.4 (width) × 4.9 (height); 0.5 slope on face | $73^d$ | 2.3 | 0.3 | New England Division, U.S. Army Corps of Engineers | Also 6.9-m-high weir; three cribs |
| **Rock-filled scow** | 3-17 | icr | St. Marys R. | Steel; stone | 7.3 × 24.3 | $50^c$ | 1.8 | 0.5 | Detroit District, U.S. Army Corps of Engineers | Supplemental anchors |
| **Crane weights** | | icr | St. Marys R. | Reinforced concrete | 3.3 × 3.3 × 3.7; stack of six weights | $58^c$ | 1.8 | 0.5 | Detroit District, U.S. Army Corps of Engineers | Supplemental to scow |
| **Weirs** | 3-23 | icfs | Small streams | Logs; steel | 30–61 (pool length) | Hydrostatic pressure | 1.5 | Unknown | Bureau of Reclamation, Engineering & Research Center, Denver | |
| | 3-24 | icfs, x | Israel R. | Stone; gabion basket | 2 (height) × 52 (length) | 88 at crest | 2.1 | <0.1 | New England Division, U.S. Army Corps of Engineers | Local protection project |
| **Weir and grating** | 3-25 | icfs | Chaudiere R. | Concrete piers; steel grill | 12.8 (height) × 190 (length) | Unknown | 8.2 | Unknown | Quebec Ministry of Natural Resources, St. Georges, Quebec | |

*icfs = ice cover formation and stabilization
ijr = ice jam reduction
icr = ice cover retention
ir = ice retention
d = shear or diversion
n = navigation
p = hydroelectric power
x = experimental
†d = design criterion
c = estimated

**Figure 3-12. Montreal ice-control structure (looking southwest and upstream); LaPrairie Basin is in the background**

the same hydraulic factors as the other booms. Owing to continued operational difficulty, the boom units were eventually removed. The piers alone were found to be adequate to form an upstream ice cover.

(2) Reinforced concrete beams of great depth are used at some reservoirs to restrain ice while water is being discharged over a spillway or into a canal. The spillway barrier shown in Figure 3-13 is located on the Sigalda power project reservoir on the Tungnaa River in Iceland, about 160 km (100 miles) east of Reykjavik. The space below it provides 4.9 meters (16 feet) of clearance. Ice remains naturally on the reservoir under all but the most severe flood conditions. The barrier is designed to retain ice during the latter low-frequency, high-discharge events. Three miles (4.8 kilometers) downstream of Sigalda, a boom protects the entrance to the power canal of the Hraunyjafoss power project. During periods of frazil ice generation, the frazil agglomerations collect at the reinforced concrete boom (Figure 3-14). The structure functions as a shear boom when a portion of the river flow is used to convey the frazil ice over an adjacent, gated sluiceway. Model studies showed that the deep, fixed boom would be more effective at keeping ice from the power canal than was a large (but relatively smaller) floating timber boom. Fixed structures such as these are useful where the water level changes little. If seiches are large or the operation of ships is an important consideration, then a fixed boom would probably not be appropriate.

*b. Stone groins.* A groin is usually a rigid structure built out from shore to protect it from erosion, to trap sediment, or to direct the flow. Groin arrangements have been used for ice control at the Manasan Falls control structure on the Burntwood River in northern Manitoba, Canada, and at Hestefoss on the upper Pasvik River in northern Norway. At both places there are groins opposite each other across the river, and the Pasvik system has additional groins. Both arrangements are supplemented by ice booms upstream of the groins.

(1) The Burntwood River was made part of the Churchill River Diversion, and its flows in winter were increased from 28 to 850 $m^3/s$ (990 to 30,000 $ft^3/s$). Model studies indicated that frazil ice generation in the reach above Manasan Falls could lead to hanging dams, ice jams, and flooding in

**Figure 3-13. Fixed ice boom at Sigalda Reservoir, Tungnaa River, Iceland**

Thompson, a city 6.4 kilometers (4 miles) downstream. The control structure at Manasan Falls was constructed to increase the upstream water levels sufficiently to promote the formation of a stable ice cover. It consists of two rock-filled groins creating a trapezoidal opening (Figure 3-15). The two groins have upstream filters and seals, and the ends of the groins were protected by 0.9- to 1.2-meter-diameter (3- to 4-foot-diameter) armor rockfill. The armoring material has remained stable at flows up to 850 $m^3/s$ (30,000 $ft^3/s$) and at average water velocities in the gap exceeding 5.8 m/s (19 ft/s). The channel constriction provides the required stage and velocity conditions for upstream ice cover formation behind a boom. A larger hydroelectric dam planned for a nearby site will provide the ultimate solution to the problem.

(2) On the Pasvik River, a substantial amount of frazil and anchor ice is formed in the reach above the powerhouse at Hestefoss. Natural anchor ice dams as high as 3 meters (10 feet) can form, but they are poorly anchored to the riverbed and can break, causing heavy ice and transient water flows. The river was made narrower in the rapids area by installing stone groins to promote ice bridging and to stabilize the ice dams (Figure 3-16). To reduce the surface area of open water and the amount of anchor ice, timber booms were installed above the rapids and a plastic pipe boom was installed below the rapids in the forebay of the powerhouse. In 1970, after 2 years of observations, the stone groins were functioning as expected.

(3) The technology for groins is described in shore protection manuals. The applications described for ice are not as simple as they seem, but groins may be the least expensive and most reliable method of ice control at a particular site.

*c. Removable gravity structures.* A problem developed with the St. Marys River ice-control boom in the harbor at Sault Ste. Marie, Michigan, because the ice cover above the west arm of the boom would break free from shore and move laterally into the open ship track. Although the loads from the ice sheet were within the expected range, their distribution was different enough to cause damage when the boom timbers were frozen solidly into the ice cover. Damage could be prevented if the ice cover could be kept

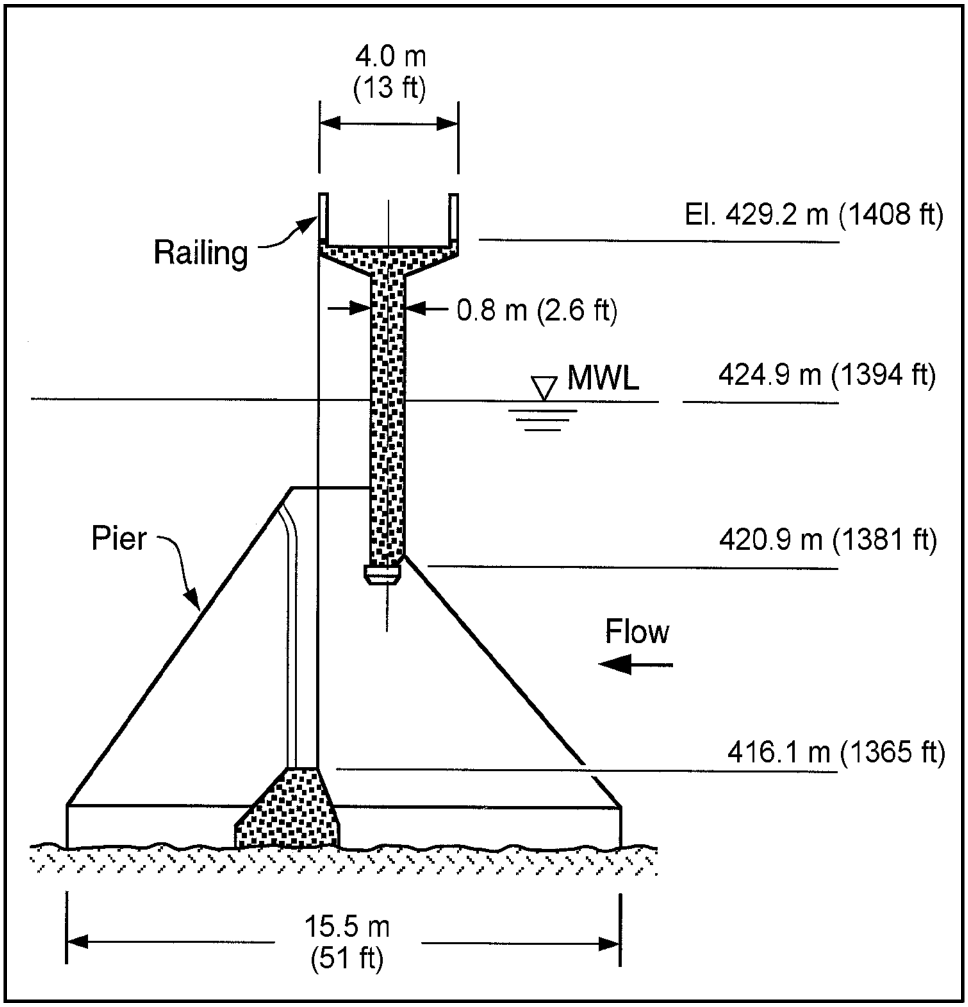



**Figure 3-14. Inlet structure at Hraunyjafoss Power Canal, Tungnaa River, Canada**

from rotating. The only method that could be used at that time was a removable gravity structure. The main structure used was a scow, surcharged to a total weight of $2.45 \times 10^5$ kilograms (270 tons) and sunk in shallow water (Figure 3-17). The scow was also secured with ship anchors. In the spring it was refloated and moved away. The method has worked very well.

(1) Later, observers noticed that sewage plant effluents weakened part of this ice cover on the St. Marys River. Thus, the ice-holding capability of the scow was supplemented by placing a stack of crane weights in the shallow water of Soo Harbor, about halfway between the scow and the ice boom. The reinforced concrete crane weights key together when stacked and are bound into a unit by wire ropes. The six crane weights weigh a total of $8.6 \times 10^4$ kilograms (95 tons). They helped to reduce the rotating ice sheet problem to a manageable level.

(2) The holding force available from gravity devices depends not only on the weight of the device in water but also on the coefficient of friction between the device and the bottom; a value of 0.3 was used in the Soo Harbor analysis. The force level was estimated from the expected action of water and wind drag

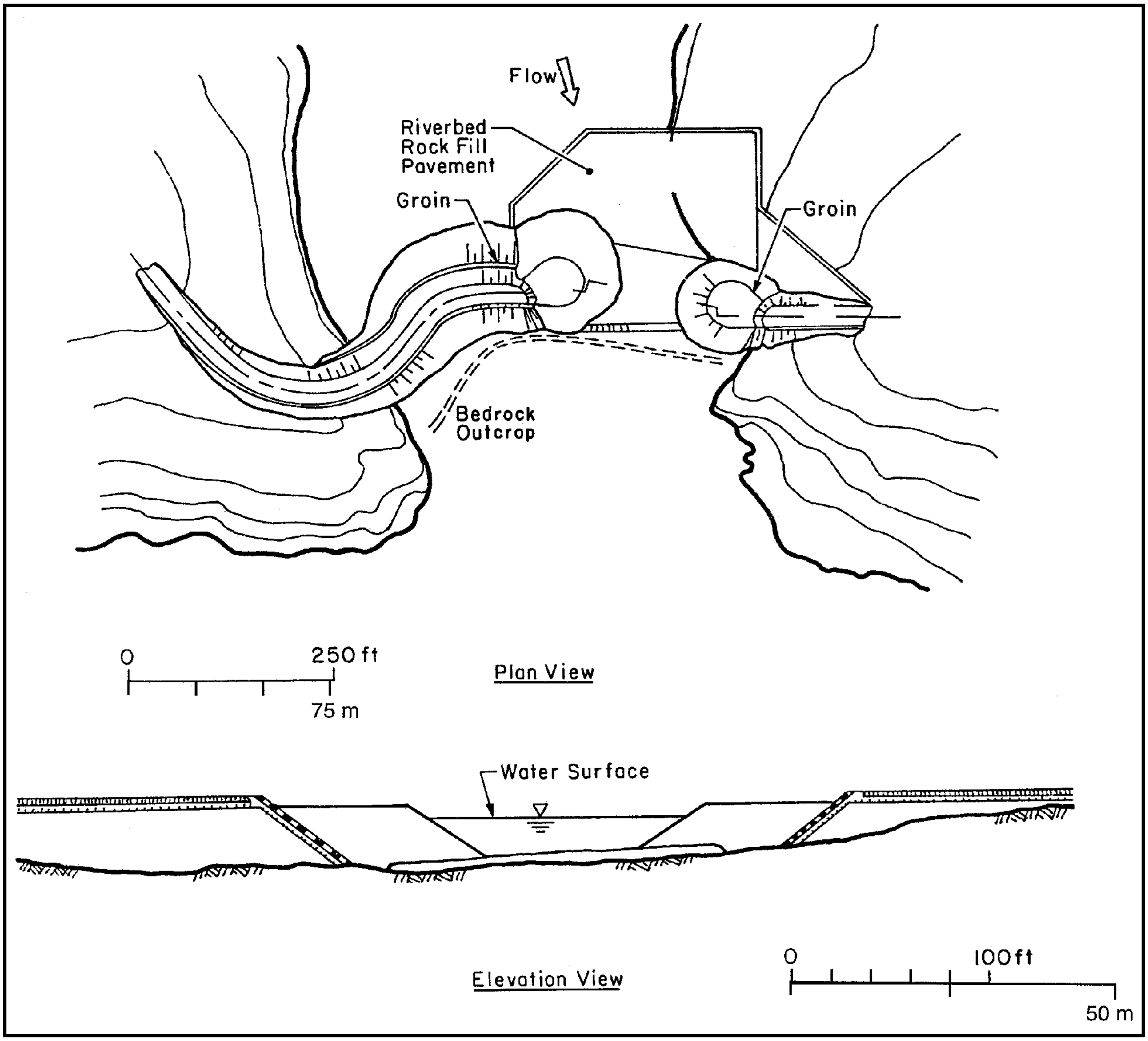



**Figure 3-15. Ice-control groins and booms on the Burntwood River, Manitoba, Canada**

on the maximum expected ice sheet. Eventually, all the removable devices in Soo Harbor were replaced by artificial islands.

*d. Artificial islands.* In the same manner that natural islands help hold ice in place, artificial islands can be used to help form, stabilize, and retain an ice cover in certain locations. One example is the Lake St. Peter section of the St. Lawrence River, about 80 kilometers (50 miles) downstream of Montreal, Canada (Figure 3-18). Lake St. Peter is about 13 kilometers (8 miles) wide and 32 kilometers (20 miles) long and has an average depth of 3 meters (10 feet). Passing through the middle of the lake is a 244-meter-wide (800-foot-wide) navigation channel dredged to a depth of 10.7 meters (35 feet). The water flow velocity in most of the lake averages about 0.3 m/s (1.0 ft/s), while in the channel it is 0.5 m/s (1.6 ft/s).

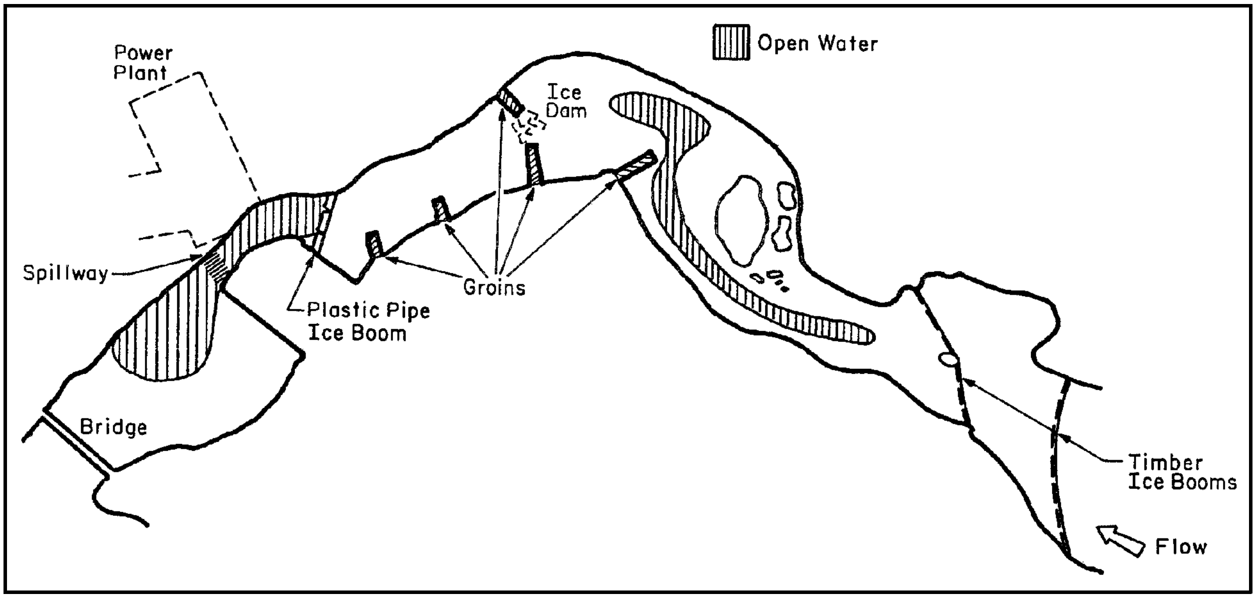



**Figure 3-16. Ice-control groins and booms on the Pasvik River, Hestefoss, Norway (showing the maximum ice conditions ) early March)**

**Figure 3-17. Rock-filled scow stabilizing the ice cover is Soo Harbor, Michigan**

(1) To prevent floods in Montreal Harbor, a passageway for ice floes, slush, and frazil ice is maintained by icebreakers from Montreal Harbor to Quebec City. At times, however, ice sheets would break free and be moved by wind and water to clog the passageway. Occasionally, a strong northeast wind would move the floating ice back upstream. Some light-tower bases helped hold the ice, but more stabilization was needed.

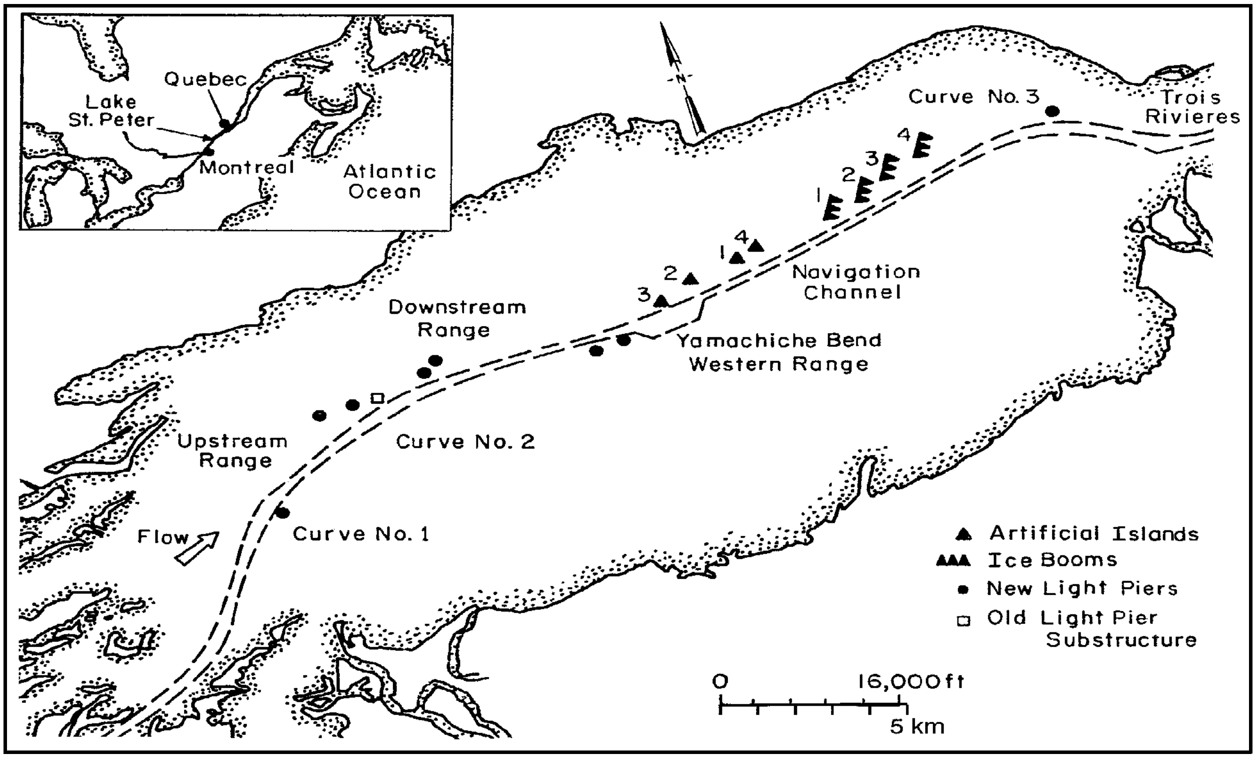



**Figure 3-18. General plan and location of artificial islands, ice booms, and light pier in Lake St. Peter, St. Lawrence River**

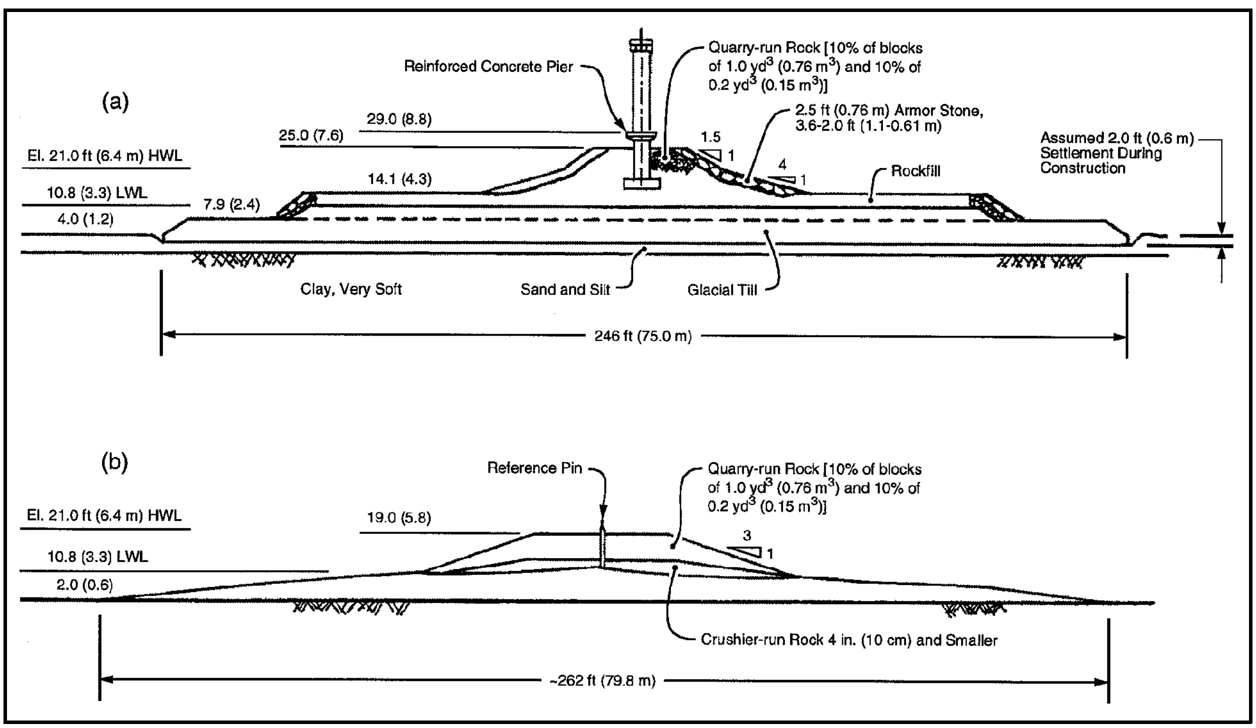



**Figure 3-19. Cross sections of artificial islands in Lake St. Peter**

(2) Several ice-control structures were evaluated in various parts of Lake St. Peter and at Lavaltrie, upstream in the river. Ice booms were successful but pile clusters did not perform well because the lake bed was probably too weak for the pilings to sustain the high ice forces. Artificial islands of three types were built to anchor the ice cover. The most stable type for the existing conditions is shown in Figure 3-19a. The second type (Figure 3-19b), which cost much less to build, is only as high as the mean winter high water level. A third type was formed by placing riprap around the substructures of old light piers. The islands were successful in forming and retaining a stable ice cover, and the winter navigation season was increased by an average of 30 days. In more recent years, additional islands and booms have been installed, and navigation to Montreal now lasts the entire winter. The islands, especially the low ones, require maintenance because the foundations have settled and the slopes have been eroded by moving ice.

(3) In 1980 three artificial islands were constructed in Lake St. Louis on the St. Lawrence River, upstream of Montreal. The islands are permanent and located east of Ile Perrot and north of the navigation channel (Figure 3-20). The islands were designed and constructed to help stabilize the ice cover north of the navigation channel, particularly during the spring breakup and the opening of the navigation season, eliminating the problem of large ice floes obstructing navigation. The effectiveness of the artificial islands has not been fully assessed.

(4) Artificial islands have been helpful in some locations, but they were chosen only after the ice movements had been studied. These islands provide good lateral stability to the ice cover, but a small change in water elevation will fracture the ice near the islands. Ice on the lee side may move away from the island, but ice on the windward side will remain in position. Islands armored with stone cost more initially but have lower maintenance costs.

*e. Timber cribs.* Timber cribs are enclosed frameworks built of timber and packed with stone to make strong, stable structures. Many small dams were built using this type of construction and have lasted for 80 years or more. Log boom docks are usually stone-filled timber cribs.

(1) An example of ice-restraining timber cribs is at the Narragaugus River flood control project, 1.6 kilometers (1 mile) upstream of the seacoast town of Cherryfield, Maine (Figure 3-21). The upstream face of each crib is sloped. Treated timbers were used in the construction. Three cribs are located in a triangular pattern about 38 meters (125 feet) upstream of a 2.1-meter-high (7-foot-high) dam and spillway. The ice cover normally contacts the crib at approximately midheight. The effectiveness of the timber cribs has not been measured, but they have remained in good condition for over 20 years. During this period severe ice jams have not occurred in the town, but the contribution of the timber cribs is unknown. The dam is undoubtedly the most important part of the project; the importance of the delay in ice cover movement at the dam caused by the cribs depends greatly on the tide water level.

(2) Timber cribs have been used to support navigation light towers in several locations, such as Lake St. Francis and Lake St. Peter near Montreal on the St. Lawrence River. In this capacity, they have also helped to keep the ice cover in place, but their usefulness on large lakes is in doubt. On poor foundation material, the crib is supported by timber pilings (Figure 3-22). Four small light piers were built on this type of subsurface structure in 1958 in Lake St. Francis. After receiving structural damage from ice thrust, more piles were added and the concrete cap was changed from a flat slab to a smaller cylinder. The resistance to ice thrust based on a stability analysis was thus increased to between 2.9 and $4.6 \times 10^4$ kg/m (between 10 and 15.5 tons/ft). Later, however, the cribs were replaced by conical, concrete light piers designed for a much larger ice force of $1.52 \times 10^5$ kg/m (51 tons/ft).

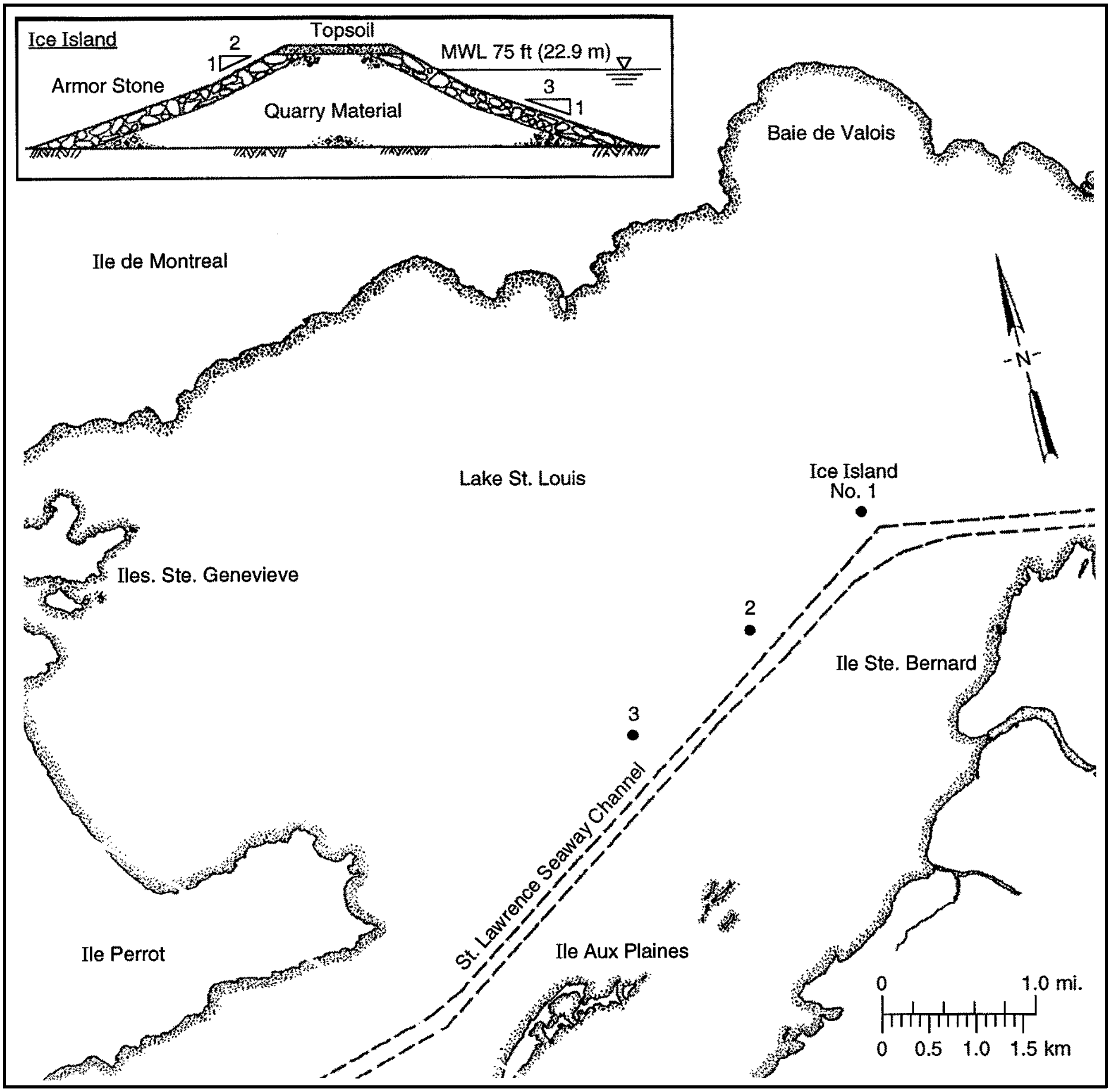



**Figure 3-20. Artificial islands in Lake St. Louis, St. Lawrence River**

*f. Weirs.* Weirs are low-head dams built across streams to raise the water level. A weir of sufficient height forms a diversion pool with the low velocities that permit the formation of an ice cover. This, in turn, precludes the formation of frazil ice and anchor ice. The ice cover is restrained by the streambanks and the structure because of the narrow width. The weir can be built from stone, concrete, or timbers (Figure 3-23). A common feature is the capability of adding flashboards or stop logs to increase water levels for winter operations.

(1) The performance of a low-head weir as an ice-control structure was observed by U.S. Army Corps of Engineers personnel on the Israel River in New Hampshire (Figure 3-24). The site was once the location of a small hydropower dam. The weir was constructed using rock-filled gabion baskets containing an impervious sheet piling and covered by a concrete cap. The low-flow discharge passes

**Figure 3-21. Ice-holding timber cribs in the Narragaugus River, Maine**

through four 1.2-meter-wide (4-foot-wide) spillways. Indications were that the weir has only a small influence on the ice regime of the river.

(2) Weirs can help other structures to promote the formation of an ice cover by reducing the local flow velocities in the pool. An ice-control arrangement in the St. Lawrence River at Massena, New York, used a stone weir to raise the water level at an ice-control boom. The stones had to be about 1.5 meters (5 feet) in diameter to be stable. The boom consisted of a series of floating scows positioned between timber cribs. The flow velocities were 3.0 to 4.6 m/s (10 to 15 ft/s). Construction of the St. Lawrence Seaway project in the late 1950s eliminated this site.

(3) A 12-meter-high (40-foot-high) ice-control dam (Figure 3-25) was built on the Chaudiere River at St. George, Quebec. Upstream of the spillway section, ice gratings fixed between concrete piers retain ice floes. The gratings, however, are located far enough upstream of the weir crest to have little effect on the weir's performance. Operable gates to one side of the spillway section are used to maintain a fairly constant pool elevation.

*g. Pilings and dolphins.* Piles that support a wharf or pier can anchor or retain an ice sheet. The effects of the vertical uplifting forces and horizontal forces from ice sheets must be considered for structures using exposed pilings. Piling clusters, or dolphins, have received greater consideration for restraining ice. These are usually formed by a cluster of closely driven piles secured at the top with wire rope. Model tests of a line of individual pile clusters indicate that good ice retention is possible. An installation of several timber clusters in Lake St. Peter in 1962, however, failed early in winter. The cause was attributed mainly to a very weak foundation and large ice forces. Tests show that dolphins have surprisingly little resistance to steady lateral pulls.

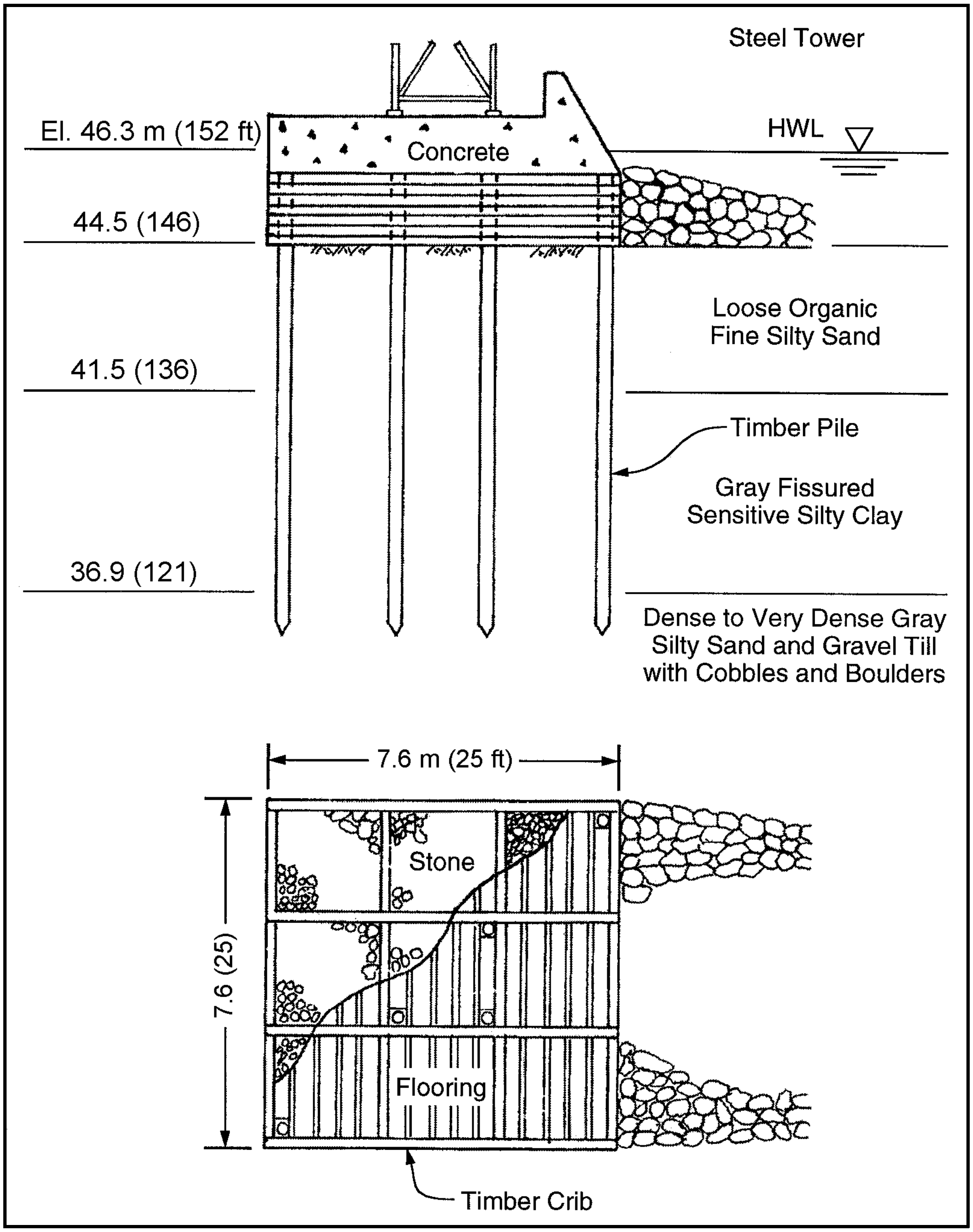



**Figure 3-22. Stone-filled timber cribs and concrete caps used as light tower bases**

(1) A dolphin in the Cap Cod Canal, Massachusetts, resisted ice forces for several years but eventually failed from the action of ice floes moving in water currents with velocities up to 3 m/s (10 ft/s). The replacement dolphin in the 10-meter-deep (33-foot-deep) water was made of 21 steel H-piles.

(2) Besides vertical and horizontal forces, the effect of ice abrasion is an important consideration. It is possible for ice to sever timber pilings in a matter of hours. Oak pilings are fairly ice resistant, but timber structures may last only about 20 years, partly as a result of ice abrasion. Timbers can be protected

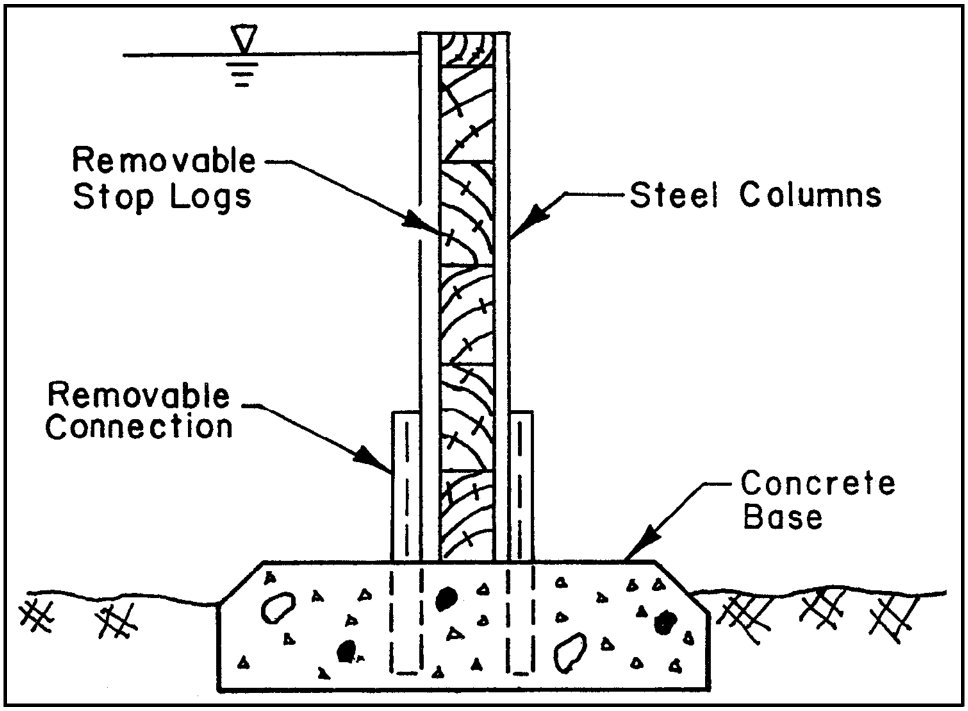



Figure 3-23. Timber weir

Figure 3-24. Ice-control weir, 2.0 meters (6.5 feet) high, on the Israel River, New Hampshire, with a moderate flow passing over the top

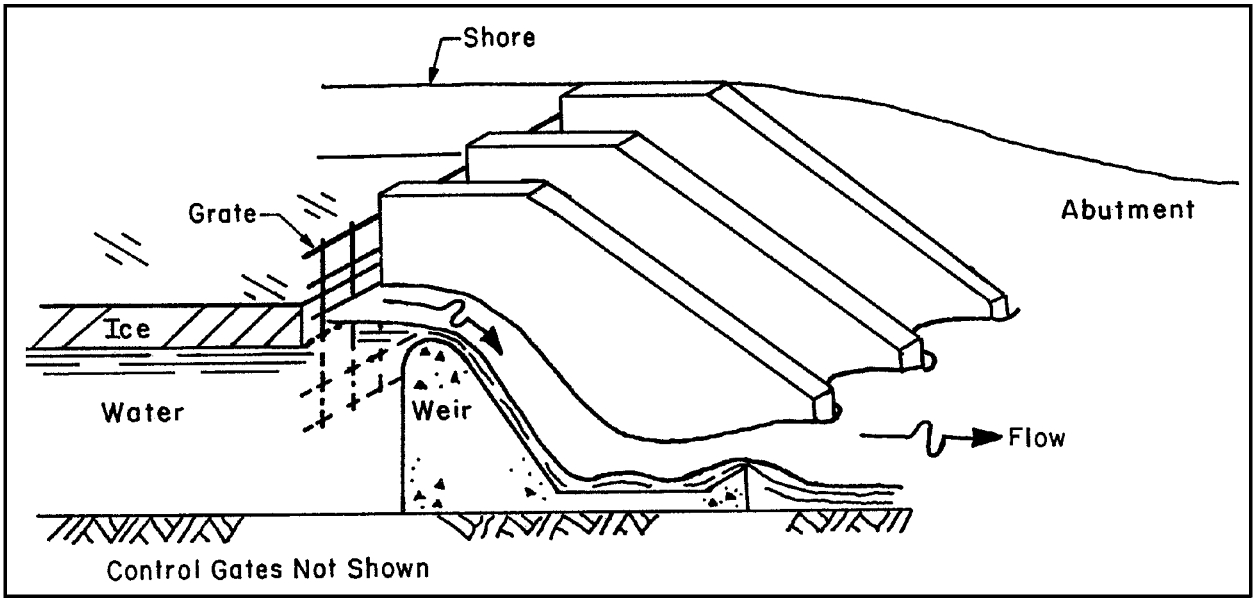



**Figure 3-25. Weir and stationary grating on the Chaudiere River, Quebec, Canada**

by steel armor. Concrete can also be adversely affected by ice abrasion and by the spalling of material from repetitive freezing and thawing of ice on its surface.

*h. Ice piers.* Ice piers are structures set in the river to protect a fleeting area against moving ice. The piers take the brunt of the impact and pressure forces and either stop the ice or deflect it to move around the ice pier location. Barges and tows are anchored downstream of the ice piers, which have anchoring chains for this purpose. The piers may be rectangular reinforced concrete structures, 4.9 × 7.6 × 3.0 meters (16 × 25 × 10 feet) high above water, or they may be similar to cylindrical sheet piling cells as in Figure 3-26.

*i. Drift deflectors.* A drift deflector is usually a barge or barges set on a diagonal with one end against the shore to deflect material floating with the currents outwardly away from shore. This method is seen to work well on the inside of bends, where the normal water currents have a natural component away from the shore. A fleeting area immediately downstream could be protected by a drift deflector. A large ice deflector arrangement was proposed for installation (but not built) at Montgomery Locks and Dam, on the Ohio River, to reduce the amount of ice entering the lock during winter navigation. As shown in Figure 3-27, three barges and a mechanical linkage type of anchoring were proposed. A towboat was to move it between its open and closed positions and also break ice. A similar function is sometimes provided by barge tows on the Mississippi River waiting for lockage at Chain of Rocks Canal and at Lock and Dam No. 17. Ice passage at these sites is no problem.

## 3-4. Ice Control by Structures Built for Other Purposes

The formation and retention of ice covers can be aided by structures that were not built for that purpose. Flows at any dam with discharge regulation capability can be manipulated to help an ice cover form. Other structures, such as wicket dams and bridge piers, aid in the formation and retention of ice covers simply by their presence.

**Figure 3-26. Cylindrical sheet piling mooring cells upstream of a navigation dam can help to stabilize the ice cover in winter**

*a. Hydroelectric dams.* It is possible to aid the formation of an ice cover on rivers by increasing flow depths and decreasing flow velocities at strategic times during the early winter. This capability must be accompanied by a comprehensive understanding of the hydraulics and ice conditions on the river and how it responds to various meteorological influences. Usually, ice sheet retention structures are needed too.

(1) An example is the operation of the Beauharnois Canal and powerhouse on the St. Lawrence River about 40 kilometers (25 miles) west of Montreal, Quebec. Here, the Coteau diversion structure sends nearly all the flow of the St. Lawrence River at Lake St. Francis down the 24- kilometer-long by 914-meter-wide (15-mile-long by 3000-foot-wide) canal to pass through the powerhouse and into Lake St. Louis. The installed capacity of the plant is 1564 MW.

(2) The Beauharnois Canal has a forebay ice boom spanning the canal and six upstream booms that contain gaps allowing ice floes to pass through and collect at the forebay boom. The forebay boom is instrumented for forces so that the operators can tell when an ice cover is starting there, even when the canal is obscured by blizzards. In early winter, a small icebreaker breaks ice in Lake St. Francis to increase the collection of ice on the canal. At this time, average flow velocities in the canal are reduced from 0.70 to 0.46 m/s (from 2.3 to 1.5 ft/s), which allows an ice cover that is smooth on its underside to form there. Higher velocities would cause a rougher ice cover to develop, reducing power generation. The formation process takes from a week to 10 days; after the ice cover stabilizes behind the booms, the flows are increased gradually to near-summer levels, 0.70 m/s (2.3 ft/s). The short-term flow reductions are more than compensated for by improved flow conditions throughout the remainder of the winter. The force instruments monitor the stability of the ice cover throughout the winter. Over the many years it took to develop this equipment and these procedures, the power plant has improved its winter output by approximately 200 MW.

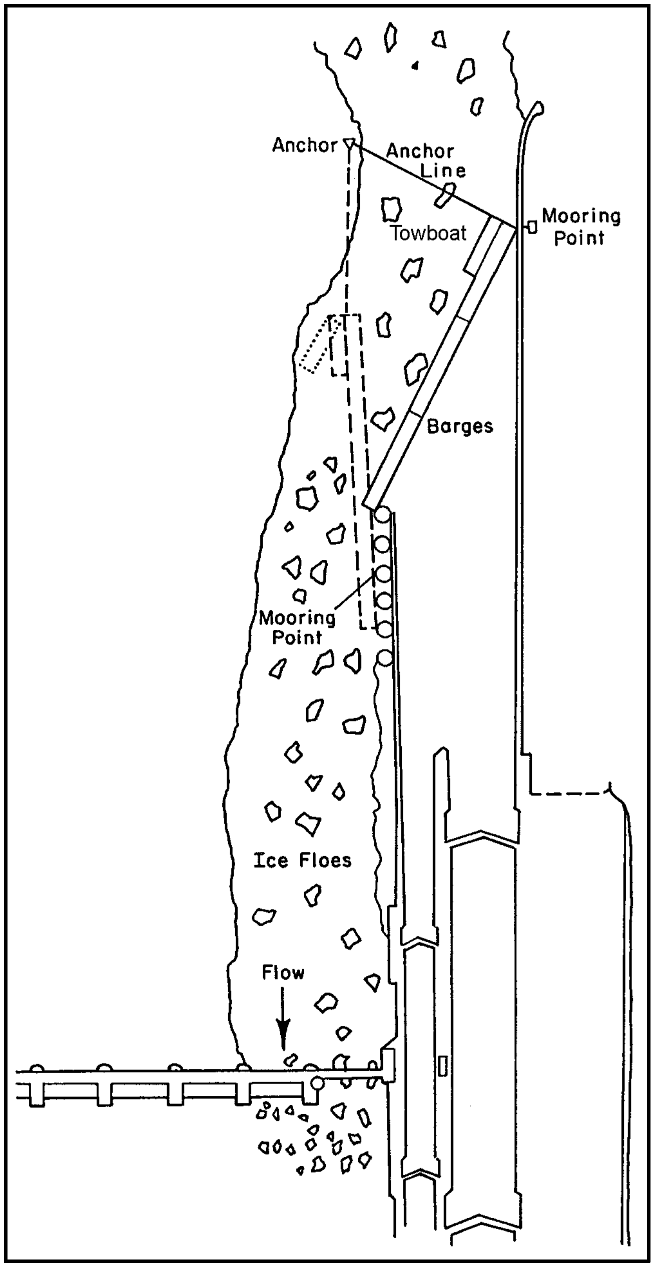



**Figure 3-27. Diagram of a proposed movable ice deflector composed of three barges and a towboat, which could be deployed to protect an upper lock entrance from ice accumulation**

(3) Another example of operator control is the International Section of the St. Lawrence River, which is controlled by the hydroelectric plants at Massena, New York, and Cornwall, Ontario. Six ice booms are located about 64 kilometers (40 miles) upstream of the dam. The progression of the ice cover is monitored closely. River flows are adjusted according to the location of the ice edge and the weather conditions so that a smooth ice cover will develop; this minimizes head losses attributable to ice during winter.

(4) As the ice edge nears the high-velocity reach a couple of miles below Iroquois Control Structure, the vertical lift gates are lowered 4.6 to 6.1 meters (15 to 20 feet) into the water. This cuts off the supply of ice floes to the downstream reach, where a hanging dam might develop. The unconsolidated ice cover continues to develop from the dam up to its local limit of the Galop Cut at Cardinal, Ontario.

*b. Wicket dams.* A wicket dam comprises a series of rectangular elements or wickets that are propped side by side and on end to form a sloping dam face (Figure 3-28). A typical wicket measures 0.3 × 1.1 × 4.9 meters (1 × 3.5 × 16 feet). The elements are raised and lowered by a barge-mounted crane, and usually they increase the upstream water level from 1.8 to 2.4 meters (6 to 8 feet). They have been used on the Ohio and Illinois Rivers for maintaining minimum depths for navigation during times of low flows. As an added benefit, these structures help to form and maintain ice covers.

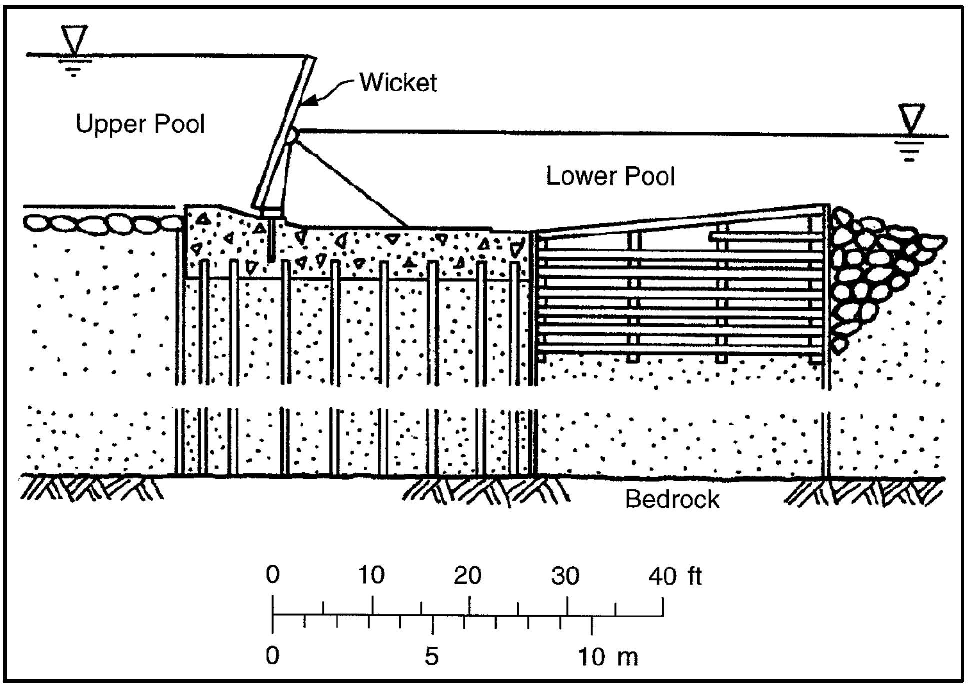



**Figure 3-28. Typical section of a navigable pass portion of a wicket dam**

*c. Light piers and towers.* Light piers and towers are used to mark the locations of navigation channels and courses. These structures can be built on land, but many are built offshore, where they become frozen into the ice sheet. Should the ice sheet break free from shore, a high force can be applied to the pier or tower. If the force is great enough, either the ice or the tower will yield. Ice loading also develops on a light pier structure when the ice on the channel side of the structure has been broken or removed while the ice cover is still intact between the light pier and the shore. The thrust is probably from thermal expansion of the solid ice.

(1) Timber cribs were used for substructures until about 20 years ago, but reinforced concrete and steel shells are now used. New light piers are usually cone-shaped where they touch the ice; the slope of the cone is usually 45 degrees. A typical light pier is shown in Figure 3-29. As in most designs where ice is involved, it is important to select a realistic design ice thickness. For this light pier, a thickness of 0.6 meters (2 feet) was selected based on previous measurements of 0.46 to 0.49 meters (1.5 to 1.6 feet). More recent measurements showed, however, that ice thicknesses may reach 0.79 meters (2.6 feet); a design ice thickness of 0.9 meters (3 feet) is now used.

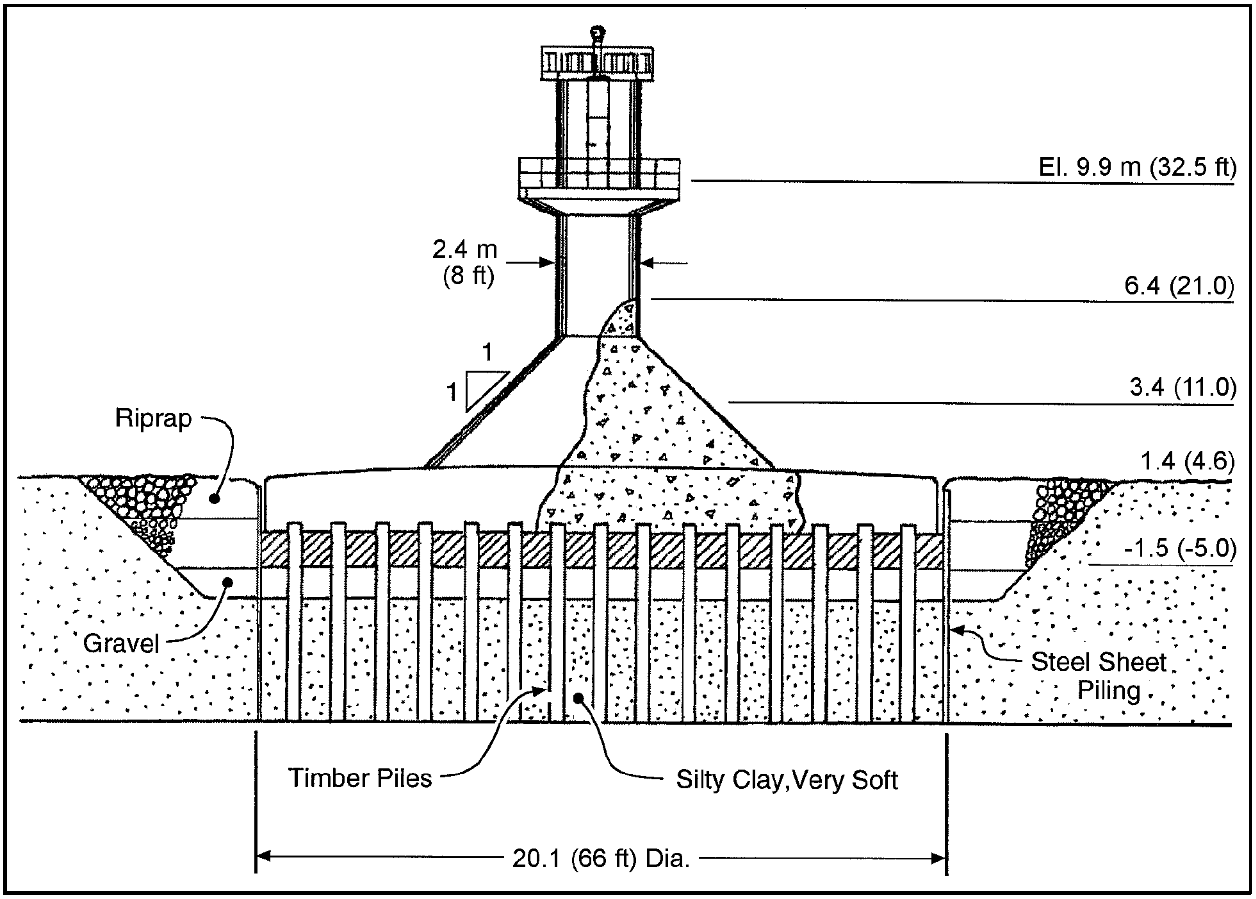



**Figure 3-29. Light pier built in 1968 on Lake St. Peter, Canada**

(2) A U.S. Coast Guard light pier that was built in Lake St. Clair is shown in Figure 3-30. The base of the light pier is stabilized by a ring of sheet steel pilings and a central arrangement of driven piles. Its conical top is welded to the upper end of the sheet piling ring. The core of the pier is filled with stone, while reinforced concrete fills the cone and the top of the pile cylinder. A relatively small tower and light are mounted on top.

(3) The all-steel light tower shown in Figure 3-31 is located about 4.8 kilometers (3 miles) offshore in Maumee Bay on Lake Erie. A key to the tower's survival is undoubtedly its large wheel-like base, which is fixed in place by several pilings.

*d. Bridge piers.* Bridge piers often constrict the river flow, and ice floes may collect at the piers in early winter to form an unconsolidated ice cover. Border ice growth on the piers can increase this narrowing effect at the water's surface if the spacing is small. Under some circumstances, however, this channel narrowing may lead to water velocities that are too high to allow an ice cover to form. Dynamic, static, and thermal ice pressures and ice abrasion must be considered in designing bridge piers.

*e. Breakwaters.* A breakwater is a structure protecting a shore area, harbor, anchorage, or basin from wave action. Stationary breakwaters can increase ice cover stability and bear the brunt of forces from moving ice that would otherwise affect the areas protected by the breakwaters. This is not generally the case with floating breakwaters.

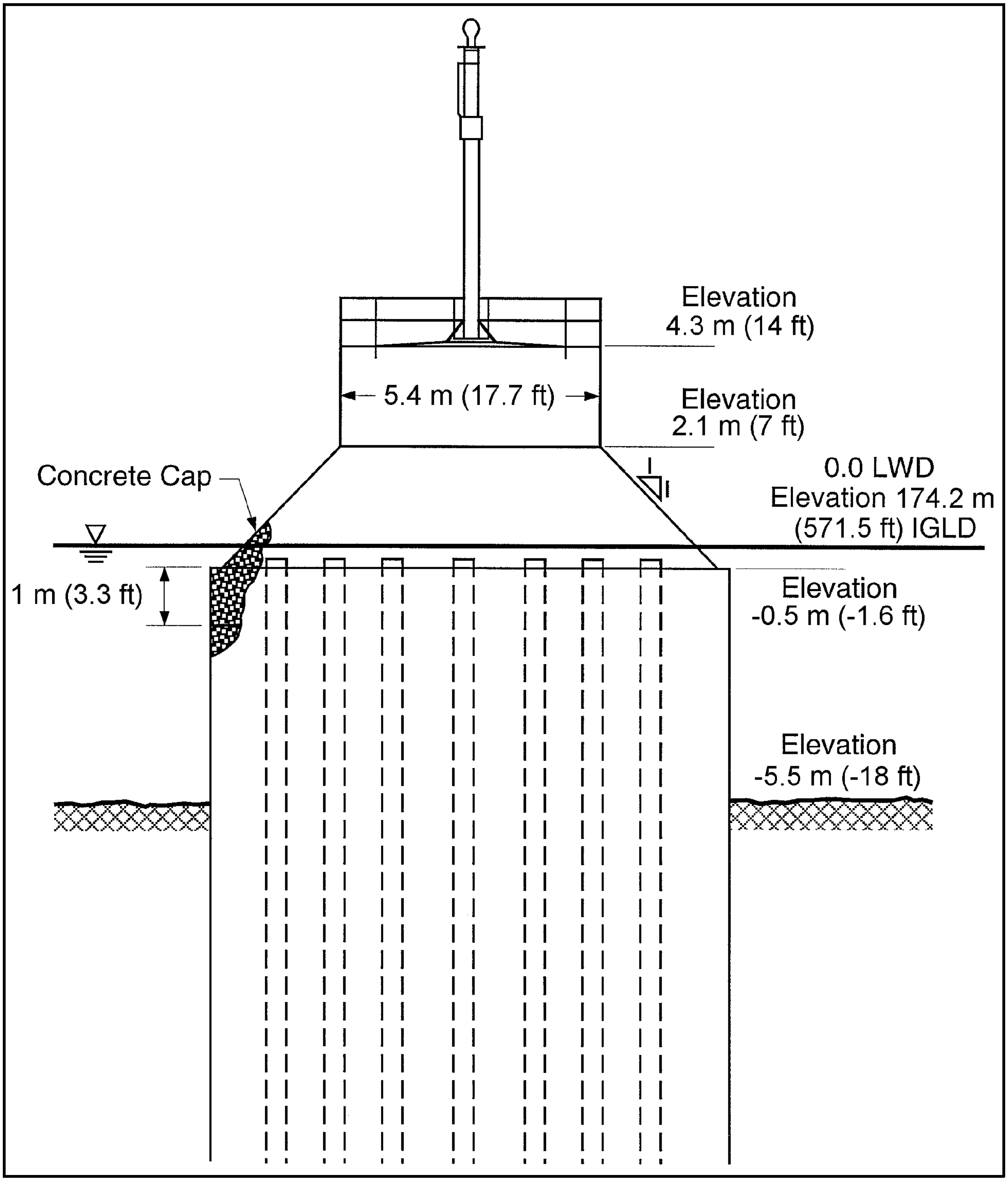



**Figure 3-30. Light pier in Lake St. Clair, Michigan**

(1) Breakwaters may be constructed from rubble mounds, cast concrete elements, concrete caissons, sheet-piling cells, or cribs, or be prefabricated and moved into place. In the United States, breakwaters built on the open coast are generally of rubble-mound construction. Occasionally, they are modified into a composite structure by using a concrete cap for stability. An innovative 5.8-meter-high (19-foot-high)

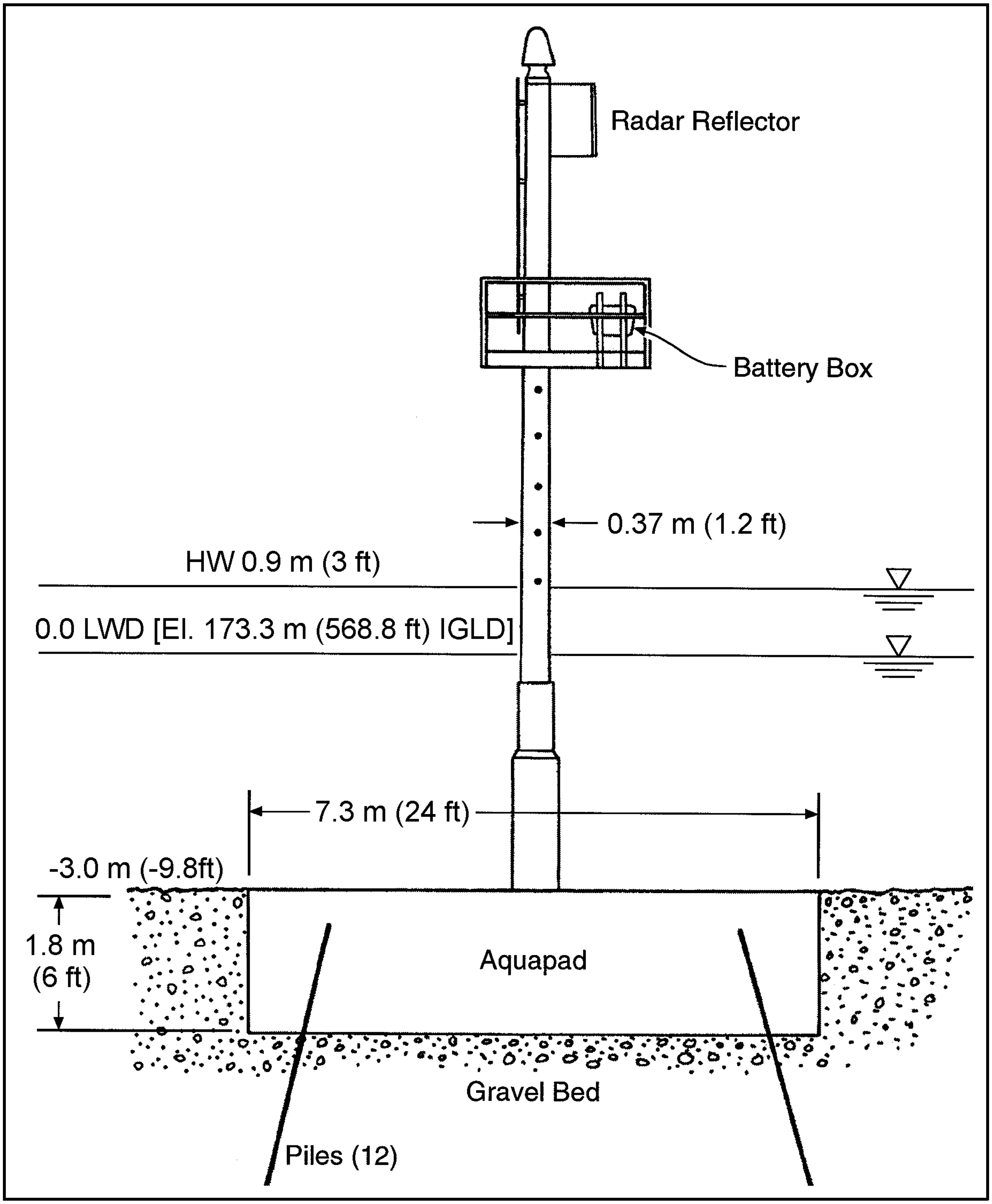



**Figure 3-31. Steel light tower on Maumee Bay, Lake Erie. The tower has a square cross section**

pack ice barrier constructed of ballasted steel pipe protects the coast line of the Saroma Lagoon in northern Japan.

(2) Normally, the wave forces on shore structures are comparable in magnitude to the maximum probable pressure that might be developed by an ice sheet. As the maximum wave forces and ice thrust cannot occur at the same time, usually no special allowance is made for overturning stability to resist ice thrust. However, where heavy ice may occur, either in the form of a solid ice sheet or floating ice fields, adequate precautions must be taken to ensure that the structure is secure against sliding on its base. Other problems such as gouging, abrasion, local failures, ice ride-up, and ice cover transport of materials exist.

## 3-5. Ice Control Not Using Structures

*a. Channel improvements.* The cost of channel improvements is usually very high, and often there are many other social and environmental factors that influence their implementation. The best way to predict how certain improvements will affect the winter operation of a waterway is to accurately simulate the present and future conditions in a physical, hydraulic model. Changes that reduce average water velocities and velocities at local points of acceleration generally help to form and maintain an ice cover. The most reliable improvements are to make the channel deeper and straighter and to remove midstream obstructions that cause high-velocity zones. However, it is important to consider the effect of channel modification on the breakup ice regime. For example, deepening the channel at a location to reduce velocity and encourage ice formation may create an initiation point for a breakup ice jam.

*b. Ice-sheet tying.* Large, broken pieces of ice can be tied together with rope to keep them from moving from one location and to another. Broken ice can be tied to shorefast ice in the manner that was used on the Mississippi River at Prairie du Chien, Wisconsin, in 1981 for an emergency ferry track. Holes were drilled through the ice about 0.9 meters (3 feet) from both sides of the crack. A forearm-sized stick of wood with a rope centrally attached was set across each hole beneath the ice. The two rope ends were tied together across the crack to make a tight connection. The ropes were tightened by twisting them with another stick (Figure 3-32). Braided rope 0.6 to 1.3 centimeters (1/4 to ½ inch) in diameter worked best. Ties spaced from 3 to 9 meters (10 to 30 feet) apart were sufficient. A line spanning several sheets provided more reliability in some instances. Unless they were covered with snow, lines frozen to the surface melted free because of solar radiation.

*c. Ice-sheet bridges.* A section of border ice can be sawed out and placed diagonally across the river. Drift ice coming from the upper reaches of the river is halted by this barrier and freezes into a solid ice cover. The purpose of bridges is to develop ice covers on rapids, where tremendous quantities of anchor ice and frazil ice are generated. In practice, the ice bridge would be created below the rapids with the idea that an ice cover would progress upstream through the rapids. This technique has been used successfully to promote ice arching at a channel constriction on the Lule River in Sweden, upstream of the Vittjarv power station. Also, U.S. Coast Guard icebreakers have dislodged large floes from Soo Harbor, Michigan, allowing them to drift to the head of Little Rapids Cut to form an ice arch.

*Section II*
*Thermal Ice Control*

## 3-6. Design of Air Bubbler Systems to Suppress Ice

Air bubbler systems can suppress ice formation and allow navigation in harbors, ports, and waterways during periods when thick ice would otherwise halt it. This section provides general guidelines useful in

**Figure 3-32. Ice sheet retention by tying with lines, Mississippi River, Prairie du Chien, Wisconsin, 1981**

design and feasibility studies of such systems, briefly describes a computer program now available at CRREL for use in detailed deicing decisions, and illustrates the nature of the suppression actually effected by a bubbler system with an example simulation.

*a. Principles of operation.* A bubbler system uses an air-driven water jet to induce convection of warm water against an ice cover, thereby melting it or suppressing its growth. Figure 3-33 presents a cross-sectional schematic view of a bubbler system. A compressor (A) delivers air into a supply line; (B) the air flows through the diffuser line (C) and is discharged through orifices distributed along its length. A plume of bubbles forms and continually entrains the surrounding water as it rises (region D). Near the surface (region E), the plume spreads under the ice cover, initially in a relatively thin layer (region F), but gradually entraining more water and dissipating (region G). Convection transfers the thermal energy contained in the water to the underside of the ice cover in regions E, F, and G, causing it to melt.

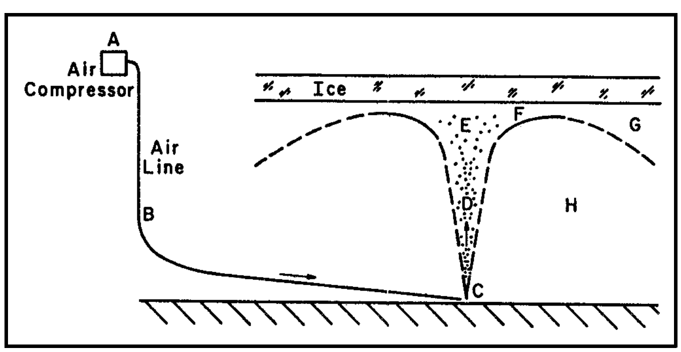



**Figure 3-33. Schematic diagram of bubbler system**

(1) The most important requirement for successful performance of an air bubbler system is a supply of warm (at least 0.2°C (32.4°F)) water. In enclosed harbors, large lakes, or connecting channels between large water bodies, winter water temperatures are generally adequate to supply the necessary thermal energy to support local suppression of an ice cover. In faster flowing rivers (mean velocity greater than about 0.4 to 0.6 m/s (1.3 to 2 ft/s)), bubbler systems cannot be expected to be very effective, for two reasons. First, in such rivers the winter water temperatures during the period of ice cover seldom exceed 0.1°C (32.2°F); hence, the thermal energy necessary for melting is not present. Second, at such velocities, the warm water flowing against the undersurface of the ice cover is already transferring heat to the ice cover as fast as a bubbler system could; hence, melting is happening as fast as it would with a bubbler system. Before a bubbler system can be designed, or the operational strategy (such as intermittent operation) formulated, measurements should be made to determine the temperatures present and the extent of the thermal reserve.

(2) Other performance requirements that must be assessed are the width of open water or extent of thin ice required for the system to be effective. Even well-operating bubbler systems with adequate warm water available will freeze over during the short periods of intense winter cold. The open water produced will seldom be as wide as the usual channel. However, for navigation the role of ice suppression is to provide a relief zone in an otherwise solid ice cover. This relief zone can be either within or to one side of the channel. Vessels can often operate effectively with such a relief zone where they could not operate in a uniformly thick ice cover.

*b. Design parameters.* Parameters that the designer of a bubbler system can control are the compressor output pressure and air discharge rate; the supply line diameter (length of which is generally dictated by the site geography); diffuser line diameter and submergence depth; and orifice diameter and spacing. The designer should realize that the various parameters interact with each other to determine the ultimate performance of a particular system.

(1) Output pressure must be sufficient to overcome the hydrostatic pressure at the diffuser line depth and the frictional losses in the supply and diffuser lines, and yet provide a pressure differential at the orifices to drive the air out at the desired rate. The required air discharge rate is determined by the system geometry (length, pipe diameters, etc.). Typical air discharge rates used in field installations have been on the order of $2.8 \times 10^{-3}$ $m^3$/minute per meter (0.03 $ft^3$/minute per foot) of line. A given system is generally either discharge-limited or pressure-limited by the compressor characteristics and system geometry. Ideally, a balanced design would result in discharge/pressure output at the peak efficiency point of the compressor's performance.

(2) The supply and diffuser line diameters should be large enough that the pressure drop attributable to friction along the line is small, so that a uniform air discharge rate can be maintained along the line. Methods exist for the iterative solution of the manifold-type problem and these methods have been incorporated in the computer simulation described below. Often, a small increase in line diameter will significantly reduce friction losses, resulting in considerably more uniform air discharge rates. Typical line diameters at field installations are between 3.8 and 7.6 centimeters (1.5 and 3 inches).

(3) Submergence depth is generally governed by operational limitations, such as depth of water body or required clearance for vessel drafts. The deeper the submergence is, the more water will be moved by a given discharge rate and hence the more suppression effected, but a larger compressor pressure is needed as the depth increases. In some cases, very large depths require pressures that make it desirable to suspend the line above the bottom.

(4) Typical orifice diameters are on the order of 0.12 centimeters (3/64 of an inch), and typical spacing is about one third of submergence depth. Orifice diameters that are too large can result in all the air leaving the diffuser line at one end. The pressure, diameter, and discharge are interrelated and cannot be easily separated from the total system design.

(5) If the far end of a diffuser line can be opened, water can be easily pumped out when the system begins operation after a shutdown. System performance is not affected by the type of pipe used (plastic or metal), so materials should be chosen on the basis of maintenance, reliability, and operational considerations.

*c. Computer simulation.* A computer simulation of the performance of an air bubbler system has been developed which allows typical winter air temperature records to be input, and it outputs the evolution of the thermal reserve, ice cover thicknesses, and width of open water. The program has been proven valid with field data obtained from an installation operated in 1974 at Howards Bay, Superior, Wisconsin. The program is written in FORTRAN, but could be easily adapted to other computer languages. The simulation is done in four parts, outlined below.

- Diffuser line analysis:

Input = diffuser and supply line lengths and diameters, orifice size and spacing, submergence depth, compressor output pressure.

Output = air discharge rates from orifices, air discharge from compressor.

- Induced plume analysis and heat transfer analysis:

Input = temperature profile at initial time.

Output = water discharge rates, impingement temperature, heat transfer rates to ice cover.

- Ice melting analysis:

Input = initial ice thickness profile, air temperature.

Output = evolution of ice cover thickness or width of open area, or both.

- Thermal reserve analysis:

Output = change in thermal reserve, new temperature profile.

*d. Example simulation.* Figures 3-34 through 3-37 show an example of the simulation results. Figure 3-34 shows the daily average air temperature variation, Figure 3-35 the initial water temperature profile, Figure 3-36 the variation in width of open water, and Figure 3-37 the variation in ice thickness at different distances from the bubbler centerline. The comparison of field observation to simulation results is shown in Figure 3-36. Note that the field installation was shut down after 45 days.

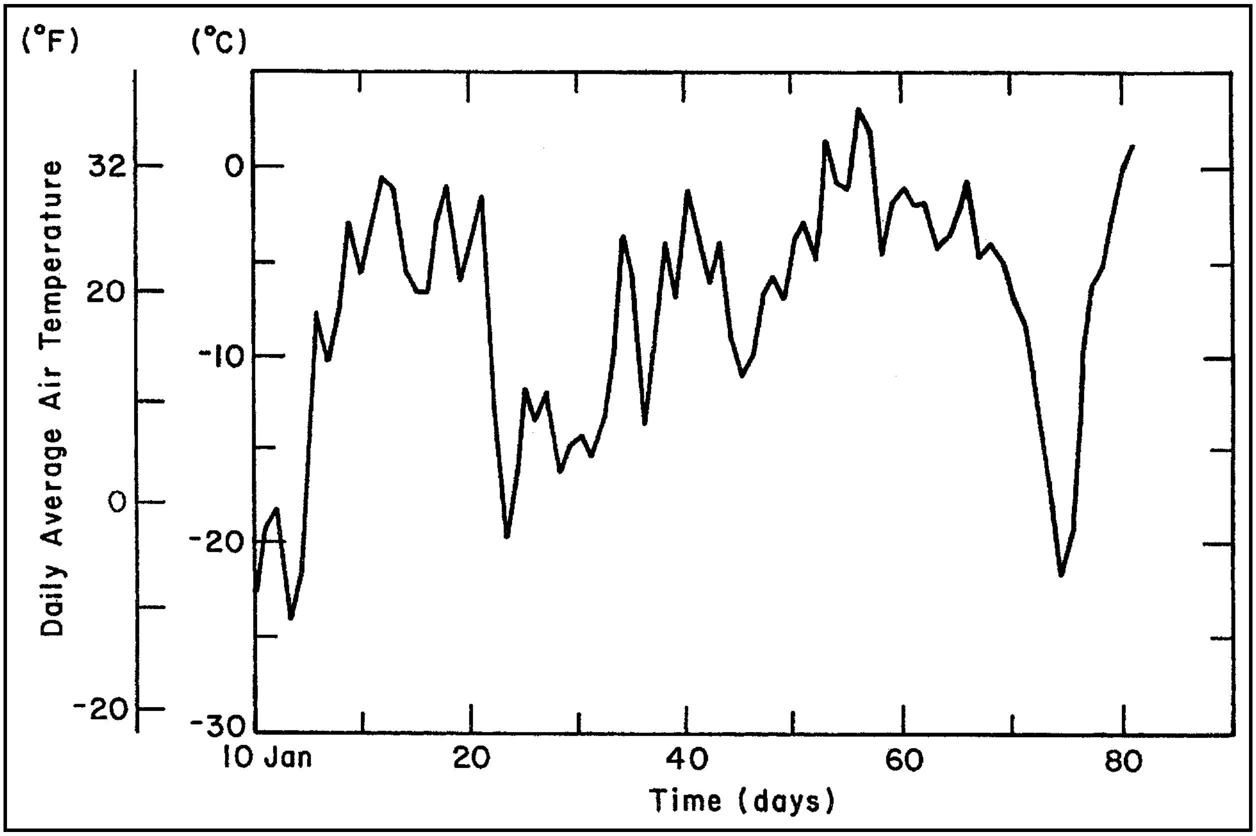



Figure 3-34. Average daily air temperatures at Superior, Wisconsin, 1974

## 3-7. Point-Source Bubbler System

"Line-source" bubblers are intended to suppress ice over long, narrow extents for uses such as navigation. Often, however, ice suppression is needed at one or more single locations, such as a pile, a local structure, or other places where a long "line" is inappropriate. A point-source bubbler can be used at such locations.

*a. Flow characteristics.* The difference between line-source and point-source bubbler systems is the geometry of the resulting flow field. The flow induced by a number of line sources tends to be two-dimensional, with the upwelling flow directed horizontally away from the line. The flow induced by a point source is conical to the surface with an outward radial flow occurring at the surface. In both cases the rate of melting, and hence the effectiveness, depends directly on the product of the water temperature and the local velocity. The velocity decreases with distance away from the location where the bubbles encounter the water surface, so that the largest melting rates occur directly above the air supply locations.

*b. Temperature requirements.* The conditions described for success of a line-source system are also necessary for the success of a point-source system. It must be emphasized that above-freezing water temperatures are required in the water body. Further, if many point sources are used, the thermal reserve in a small enclosed water body may become exhausted over the course of a winter; hence, prudent placement of a small number of bubblers is often more effective in such cases.

*c. Design.* The design parameters are much the same as for line-source systems. Information and assistance in the use of computer simulations written in FORTRAN to assess the performance of both

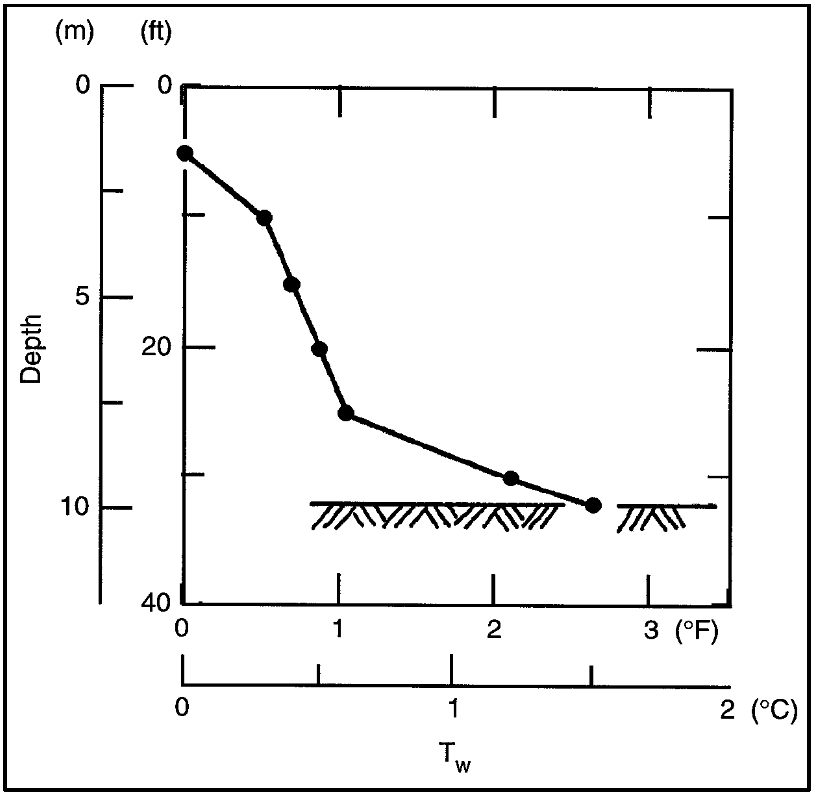



**Figure 3-35. Water temperature, Howards Bay, Wisconsin, 1974**

point-source bubblers and line-source bubblers may be obtained from CRREL. One further note is in order: it is known that the outward spreading radial surface flow will plunge below the surface at a radial distance of about six or seven times the depth. A point source bubbler will not be effective at greater distances from the air source location.

## 3-8. Use of Thermal Effluents and Warm Water for Ice Control

Most rivers have sources of warm water that either already suppress some ice formation or may be used to cause some ice suppression. The most obvious are power plants that discharge heated water into the river. Typically, there will be a narrow band of open water for some distance downstream of these plants when the river is otherwise ice covered. In other cases reservoirs, even with ice covers, may contain water above the freezing point of 0°C (32°F). When this water is released, it will flow some distance downstream before it begins to freeze. This section describes the effect on ice covers of these sources of warm water and provides approximate means of estimating this effect.

*a. Sources of warm water.* Besides the two main sources of warm water in winter mentioned above, there are other sources such as the discharge of treated sewage, warm waste water from industrial plants, and, occasionally, warm springs; but generally, all of these release too little heat to cause more than very local effects on the natural ice cover. In seeking to use warm water as an aid to river ice management, it is important to realize under what conditions the warm water may be effective, and the extent of the influence.

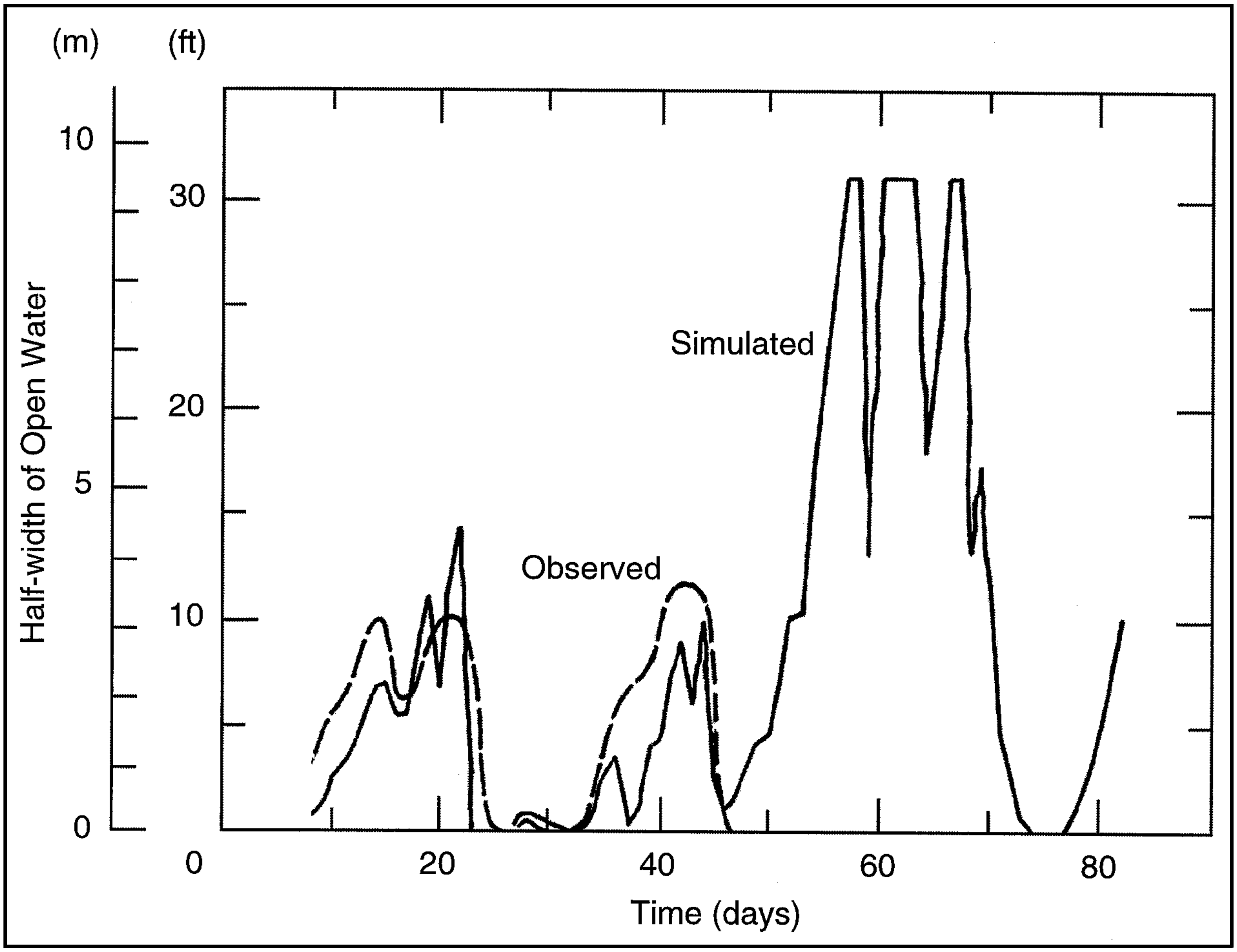



**Figure 3-36. Half-width of open water, assuming no thermal depletion, Howards Bay, Wisconsin, 1974**

(1) Both fossil fuel power plants (using coal or oil) and nuclear power plants require cooling in the process of generating electrical power. This cooling generates waste heat that is then discharged into the environment, either directly to the atmosphere by use of cooling towers, or indirectly by first discharging the heat to a water body that then transfers the heat to the atmosphere. If an existing plant already has cooling towers, it is unlikely that the plant will be able to discharge the heat to a water body because of the large capital costs of having two cooling systems. However, many plants do use rivers as the heat sink. The warm water released results in ice suppression that in some instances can be helpful in managing ice problems. Power plants operate either as base load plants, at a more or less constant capacity, or as peaking power plants to supply power at the time of greatest demand. The actual operating characteristics can only be ascertained from the utility companies directly. In Figure 3-38, the waste heat discharge of a power plant on the Mississippi River, 11 kilometers (7 miles) upstream of Lock and Dam No. 15, during January and February of 1980, is shown to illustrate the nature of the output that might be expected. During January of 1980, a large part of the plant was shut down for maintenance, and even after that the plant was not running continuously at full load. As a consequence, the waste heat discharge was variable. Nearly all plants maintain a record of input and output water temperatures, which, along with the cooling water discharge rates, enables calculation of the waste heat discharge. The waste heat discharge is determined from these data according to

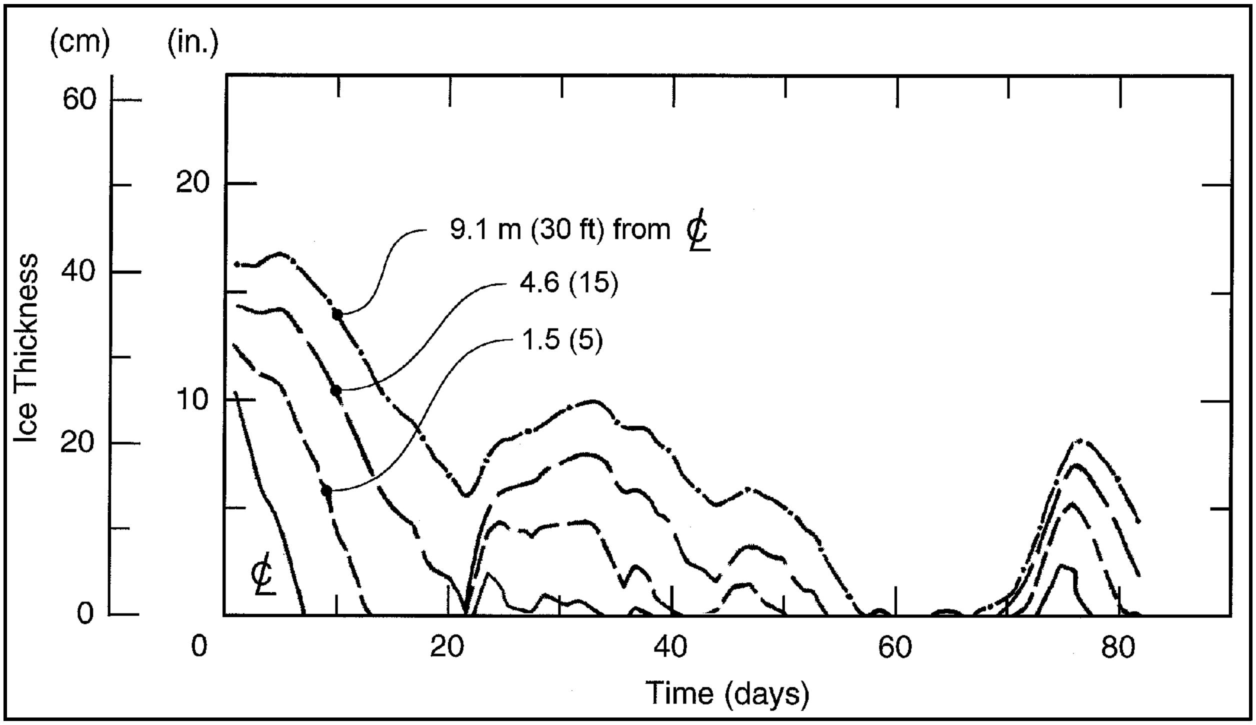



**Figure 3-37. Ice thickness, assuming no thermal depletion, Howards Bay, Wisconsin, 1974**

$$Q = \gamma C_p N(T_{out} - T_{in} \tag{3-5}$$

where

$Q$ = waste heat release rate, Btu/hr (J/hr)

$\gamma$ = specific weight of water, 62.4 lb/ft$^3$ (1000 kg/m$^3$)

$C_p$ = specific heat of water, 1.0 Btu/lb°F ($4.2 \times 10^3$ J/kg°C)

$N$ = cooling water discharge rate, ft$^3$/s (m$^3$/s)

$T_{in}$ = intake cooling water temperature, °F (°C)

$T_{out}$ = outfall cooling water temperature, °F (°C).

As an example, in early February one unit of the plant whose output is shown in Figure 3-38 had an intake temperature of 32°F (0°C), an outfall temperature of 49°F (9.4°C), and a discharge rate of 2.5 m$^3$/s (89 ft$^3$/s). Thus, in English units,

$$Q = \left(62.4 \frac{lb}{ft^3}\right) \left(1.0 \frac{Btu}{lb°F}\right) \left(\frac{89 ft^3}{s}\right) (49°F - 32°F)$$

$$= 94{,}400\, Btu/s = 340 \times 10^6\, Btu/hr, or\ in\ SI\ units, 99{,}600\, kW.$$

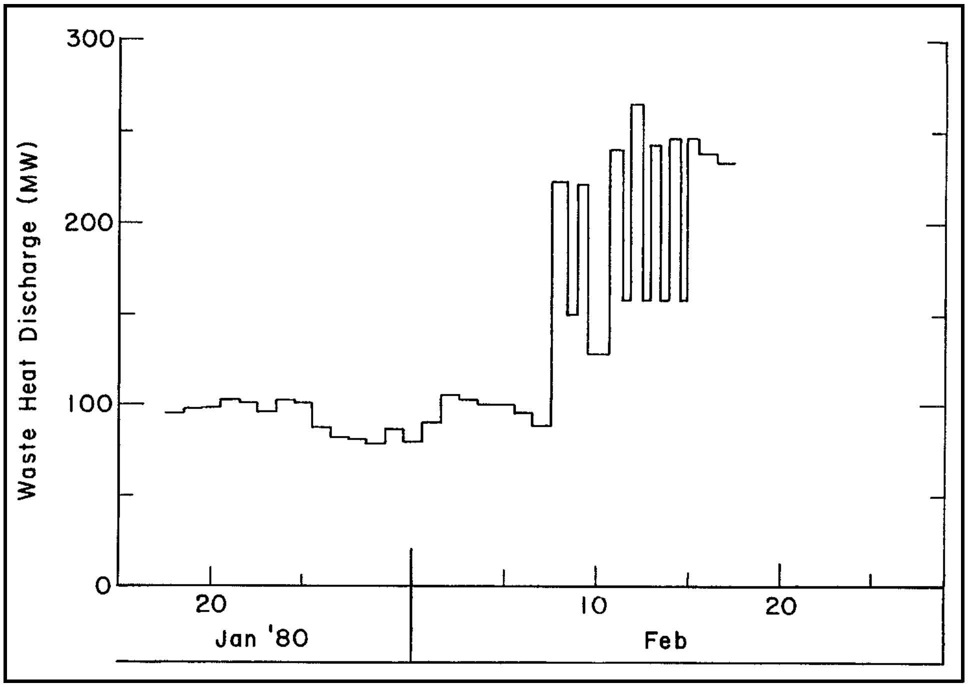



**Figure 3-38. Record of waste heat discharge from a power plant that uses Mississippi River water for cooling.** *Prior to 8 February, much of the plant was down for maintenance; thereafter, it operated alternately between full and partial load.*

This rate of energy release is greater than the electrical output of the plant, since typically coal and oil plants have 40 percent efficiency, and nuclear plants have even less at about 33 percent. Thus, coal plants discharge as heat energy to the cooling water about 1-1/2 times the amount of electrical energy put out over the transmission lines, and nuclear plants about twice as much. These ratios are useful for quick assessments of ice suppression, as will be discussed below.

(2) In many reservoirs, the water beneath the ice cover is above the freezing point. When this water is released during the winter, it takes some time and distance before it is cooled by the atmosphere down to the freezing point, after which further heat loss results in ice formation. If the warm water release encounters ice before it has cooled to the freezing point, it will melt the ice until the water is at the freezing point. The extent of melting or the distance to cool to the freezing point depends on both the release flow rate and the water temperature. This distance depends also on how cold the atmosphere is. Methods to predict the distance or extent of melting are described below. The biggest uncertainty is the temperature of the reservoir water, which is usually below the 4°C (39°F) temperature of maximum density, and depends on the particular sequence of meteorological conditions at the time of freezeup and the extent of throughflow during the winter. Water released from the bottom of reservoirs will usually be warmer than water released from near the top. Direct measurement of the release water temperature is the most certain way of assessing the flow temperature.

*b. Warm water in the context of ice production.* In the Pittsburgh District on the Ohio River, there are nine power plants that discharge warm water at a total rate of about 5500 megawatts over a distance of 201 kilometers (125 miles). At –10°C (14°F), the heat loss from open water over this reach is about 15,000 megawatts, so that the warm water reduces ice production by about 37 percent. At –20°C (–4°F), the loss from open water is about 30,000 megawatts, so the warm water reduces ice production by about 18 percent. If the ice is 5 centimeters (2 inches thick), the ice production rate under natural conditions is equivalent to a heat loss rate of about 7500 megawatts at –10°C (14°F) and 15,000 megawatts at –20°C (–4°F), so the reduced ice production is on the order of 75 percent at –10°C (14°F) and 37 percent at –20°C (–4°F). In the Huntington District there are four power plants on the Ohio River that discharge a total of 4200 megawatts over a distance of 499 km (310 miles). The heat loss from open water over this reach at –10°C (14°F) is on the order of 40,000 megawatts, so the warm water reduces ice production by about 10 percent. At –20°C (–4°F), the reduction is on the order of 5 percent.

(1) Clearly, the magnitudes of warm water discharge are small when compared with the overall energy exchange rates between the river and the atmosphere, and cannot be expected to mitigate ice problems over the entire reaches. Close to the plants, however, the suppression can be significant in affecting local ice conditions.

(2) The fact that large quantities of warm water are discharged into the river does not mean that the water temperatures are excessively high. In fact, in winter the temperatures of the warm water discharges rapidly approach the freezing point. In one observation, for example, 914 meters (3000 feet) downstream of the Riverside Power Plant on the Mississippi River, the highest water temperature in a plume from a 200-megawatt release was only 1.7°C (35°F). However, even small increases in water temperature above the freezing point can stop ice from thickening. As an example, if the air temperature is –20°C (–4°F) and the ice is 15 centimeters (6 inches) thick, the thickening rate is about 4.8 centimeters (1.9 inches) per day, if the water temperature is at the freezing point. If the water velocity is 0.46 m/s (1.5 ft/s) and the temperature is 0.089°C, or 0.089°C above freezing (32.16°F, or 0.16°F above freezing), it will stop the thickening, that is, the heat transferred to the ice from the water exactly equals the heat loss to the atmosphere. Under the same conditions, but with 30.5-centimeter-thick (12-inch-thick) ice, a water temperature of 0.06°C (32.10°F) stops further thickening. Thus, one of the effects of warm water discharge into a cold river is to limit the ice production that otherwise might occur.

## 3-9. Effects on River Ice of Warm Water Releases

Warm water effects are discussed below by first evaluating natural conditions, and then discussing various modes of heat introduction to the river.

*a. Natural conditions.* To assess the effects on river ice of a warm water discharge, it is important to appreciate the magnitude of temperatures, natural ice conditions in the river, and the heat losses to the atmosphere that cause ice formation. The water temperatures of rivers more or less follow the average air temperatures through the annual cycle until those temperatures go below the freezing point. At that time, the water, instead of cooling below the freezing point, forms ice in proportion to the heat loss to the atmosphere, and the ice acts as a buffer preventing further temperature decline. Throughout the period of ice cover, water temperatures remain very close to the freezing point, both as a consequence of turbulent mixing, which prevents stratification, and as a consequence of continually flowing past the ice cover, which is a heat sink for the river water. Only in still water or at extremely slow velocities can any significant stratification develop. There is a minor heat gain from energy stored in the bottom sediments during the preceding summer (O'Neill and Ashton 1981), and a minor gain from viscous dissipation or friction in the flow, but these gains are very small relative to the heat losses at the surface. In general, when there are significant amounts of ice present in a river, the assumption that the water temperature is at 0°C (32°F) is very accurate. This is particularly useful when assessing the effects of adding warm water, since all the energy of the warm water is used either to melt ice or is lost to the atmosphere in open water areas.

(1) Ice conditions in a river vary widely from site to site, depending on many factors. These are discussed in other chapters. From the standpoint of the effects of warm water, the ice may be classified as moving or stationary. If the ice is moving, the effect of the warm water is to reduce the volume of ice passed downstream in proportion to the amount of heat discharged. Nearly all the energy discharged into flows with moving ice is used to melt ice. In the case of an intact, stationary ice cover, the waste heat is used to melt the ice or suppress its otherwise natural thickening, as well as being directly lost to the atmosphere in the open-water areas formed by the warm water. In a sense, the open water areas formed in the ice cover act as a short circuit to the atmosphere for some of the waste heat, at least to the extent that the heat transfer rate is greater at larger values of the water-versus-air-temperature difference than would be true for an open-water surface at 0°C (32°F).

(2) This leads directly to the subject of natural heat losses from rivers in winter. Two cases are important—the open-water case and the ice-covered case. In the case of open water, the heat losses may be calculated using detailed energy budget methods, which consider the daily or diurnal variations of long wave radiation gains and losses, short wave radiation gains, sensible heat losses to the air attributable to either free convection (when the air is still) or forced convection (when the air is windy), and evaporation losses. The variables involved include time of year, time of day, latitude, air temperature, humidity, wind speed, and cloud cover. For some studies, such energy budget methods are necessary, but they involve considerable calculation effort, plus field data as input. For many studies a simpler method is adequate for estimates of the effects of warm water discharge. This method consists of simply combining all the energy budget effects into a single heat transfer coefficient applied to the difference between the water temperature and the air temperature (Ashton 1982). The heat loss per unit area of open water surface $q_{wa}$ is then given by

$$q_{wa} = H_{wa}(T_w - T_a) \tag{3-6}$$

where

$H_{wa}$ = heat transfer coefficient

$T_w$ = water temperature

$T_a$ = air temperature.

$H_{wa}$ depends on all the variables that determine the energy budget, but is typically between 15.3 and 25.6 W/m$^2$ °C (between 2.7 and 4.5 Btu/hr ft$^2$°F), with the higher values associated with higher wind speeds. As an example, if the air temperature is –12.2°C (10°F) and the water temperature is 0.56°C (33°F) and $H_{wa}$ = 19.9 W/m$^2$°C (3.5 Btu/hr ft$^2$°F), the heat loss in English units is

$$q_{wa} = 3.5 \frac{\text{Btu}}{\text{hr ft}^2\,°\text{F}} \times (33 - 10°F) = 80.5 \frac{\text{Btu}}{\text{hr ft}^2} = 256 \frac{\text{W}}{\text{m}^2} \tag{3-7}$$

(3) Once an ice cover is on top of the water, it acts to insulate the water, with the insulation effect increasing as the ice thickens. A snow layer increases the insulation effect even more. And, since the water below is at 0°C (32°F), the heat losses are directly transformed into ice production. A simple layer analysis enables estimates of the heat loss through the ice (and snow) cover. As shown in Figure 3-39, the air temperature is denoted by $T_a$, the top surface ice temperature by $T_s$, the bottom surface ice temperature by $T_m$ ,which is always at the melting–freezing temperature of 0°C (32°F). The thermal

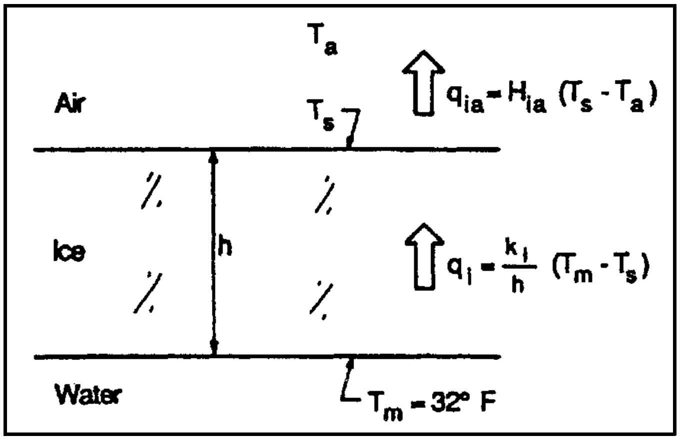



**Figure 39. Schematic diagram showing notation and heat transfer equations governing the heat flow from a water body through an ice cover to the atmosphere (32 °F = 0 °C)**

conductivity of the ice is denoted by $k_i$ and the ice thickness by $h$. It is important to note, particularly for thin ice covers, that the top surface temperature is not the same as the air temperature; if it were, there would be negligible heat loss to the atmosphere and no ice thickening. As a first approximation, which is very good for most purposes, the heat flow may be analyzed as a quasi-steady state process such that the temperature profile in the ice varies linearly from $T_m$ to $T_s$ over the thickness of the ice. The heat flow through the ice is then given by

$$q_i = \frac{k_i}{h}(T_m - T_s). \tag{3-8}$$

The heat loss to the atmosphere from the ice $q_{ia}$ can be written similar to that from an open-water surface with $T_s$ substituted for $T_w$ in Equation 3-6 to give

$$q_{ia} = H_{ia}(T_s - T_a) \tag{3-9}$$

The heat flow through the ice equals the heat loss at the surface, so that $q_{ia} = q_i$, which allows $T_s$ to be eliminated between Equations 3-8 and 3-9 and gives

$$q_i = q_{ia} = \frac{T_m - T_a}{\frac{h}{k_i} + \frac{1}{H_{ia}}}. \tag{3-10}$$

This result may be compared to the heat losses from an open-water surface to show the insulating effect of the ice cover. In Figure 3-40, the ratios of heat losses ($q_i$) through the cover to the open-water losses ($q_{wa}$) are shown as functions of ice thickness. For the range of heat transfer coefficients usually found, 15 centimeters (6 inches) of ice reduces the heat loss by 50 percent or more.

(4) This heat flux through the ice is also the heat flux upward from the bottom surface, which causes the ice to thicken at the bottom. The thickening rate is inversely proportional to the heat of fusion (***L***) times the specific weight of ice, so that the thickening rate is given by

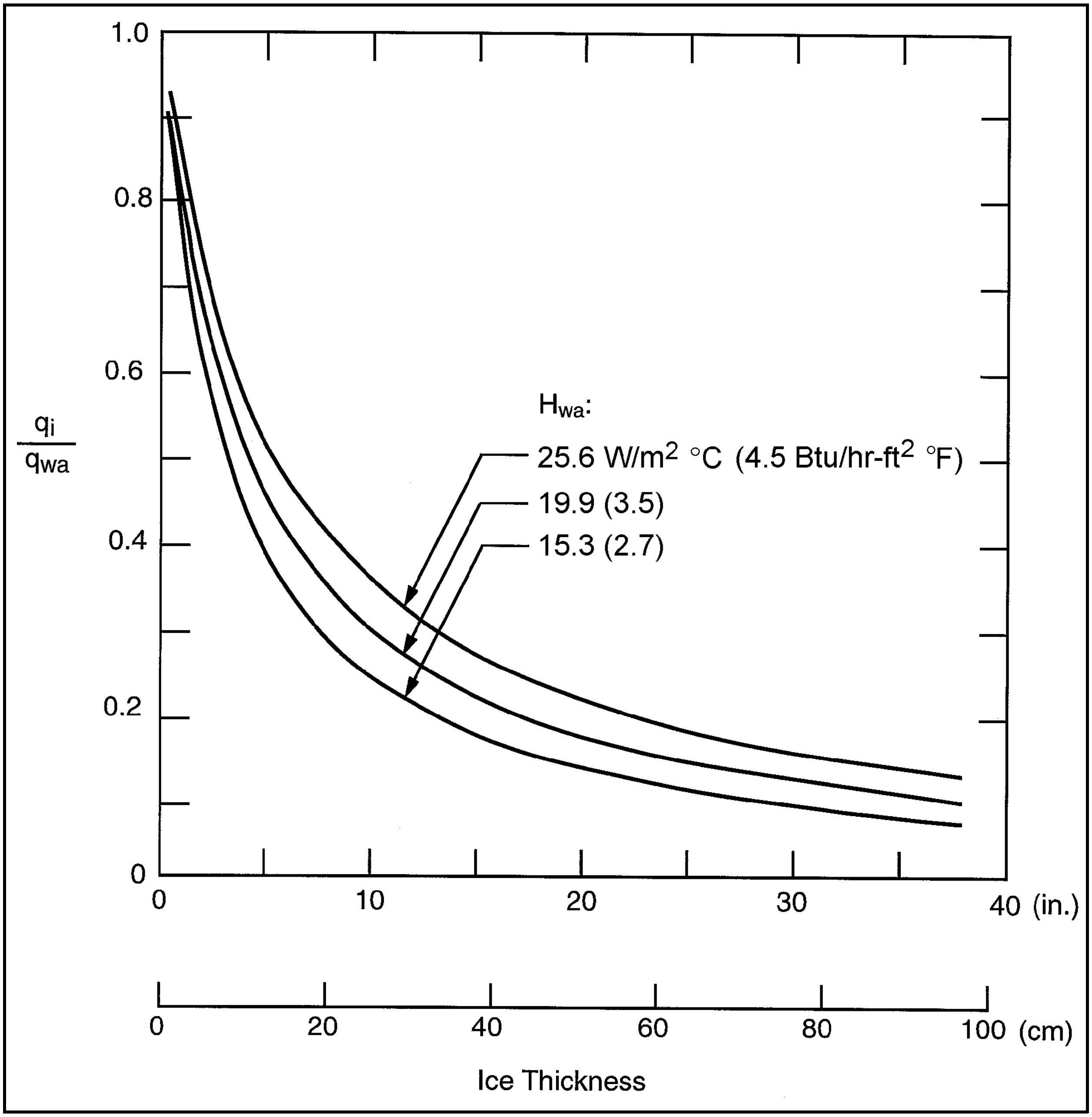



**Figure 3-40. Ratio of heat loss through ice cover ($q_i$) to heat loss from an open-water surface ($q_{wa}$) versus ice thickness, for three values of the heat transfer coefficient, $H_{wa}$ (or the equivalent $H_{ia}$ for heat transfer from ice to air)**

$$\frac{dh}{dt} = \frac{1}{\gamma_i L}\left(\frac{T_m - T_a}{\frac{h}{k_i} + \frac{1}{H_{ia}}}\right). \tag{3-11}$$

For most practical river ice problems, the specific weight $\gamma_i$, the heat of fusion $\boldsymbol{L}$, and the thermal conductivity $k_i$ may be treated as constants with values for pure ice as follows:

$\gamma_i$ = 57.2 lb/ft$^3$ (916 kg/m$^3$)

$L$ = 144 Btu/lb (3.35 × 10$^5$ J/kg)

$k_i$ = 1.30 Btu/hr ft °F (2.25 W/m °C).

Using these values gives the thickening rate

$$\frac{dh}{dt} = 0.0029 \left( \frac{T_m - T_a}{0.769h \, \frac{1}{H_{ia}}} \right) \text{ (ft/day).} \tag{3-12a}$$

In SI units, this becomes

$$\frac{dh}{dt} = 0.00028 \left( \frac{T_m - T_a}{0.444h \, \frac{1}{H_{ia}}} \right) \text{ (m/day).} \tag{3-12b}$$

As an example, for $T_m$ = 0°C (32°F), $T_a$ = –20.6°C (–5°F) (very cold), $h$ = 0.15 meters (0.5 feet), and $H_{ia}$ = 19.9 W/m$^2$°C (3.5 Btu/hr ft$^2$ °F), the thickening rate is 0.049 meters/day (0.16 feet/day) or about 5 centimeters (2 inches) per day. When the ice is 30 cm (1 foot) thick, for the same conditions, the thickening rate drops to 3 centimeters (1.2 inches) per day. Figure 3-41 shows thickening rates to be expected as functions of average daily air temperature and ice thickness, assuming $H_{ia}$ = 19.9 W/m$^2$°C (3.5 Btu/hr ft$^2$ °F).

(5) The above calculations overestimate the thickening rate, or rate of ice production, if there is a snow cover on the ice. Typically, the thermal conductivity of the snow cover is about one-tenth that of the ice cover, so it has the insulating effect of ten times its thickness of solid ice.

(6) There are several purposes to the above calculations. First, they may be used to estimate rates of ice production as a function of air temperature and ice thickness. Second, the results of the calculations show that the ice production is greatly reduced as the ice thickens, which, in turn, suggests that the effectiveness of warm water discharged into a river is greatest when the ice is thicker, since a smaller amount of heat is required to stop the growth of the ice cover. Thus, while warm water discharge may not have a great effect in preventing initial ice formation, it may have a significant effect in limiting ice production over significant reaches of the river.

(7) In summary, there are two main effects of warm water released into ice-covered rivers. First, the heat locally suppresses the ice completely and creates open-water areas near the point of release. Second, the heat acts to limit the ice thickness at regions downstream and beneath the ice cover. Both effects may be calculated using methods described below. The effectiveness of the warm water depends a great deal on specific site conditions and the nature of the ice formation that would occur otherwise.

*b. Fully mixed releases.* The water released from a reservoir is generally above freezing and completely suppresses ice for a certain distance downstream, and partially suppresses the ice further downstream beneath the ice cover. There are methods available (Ashton 1979) to simulate these effects that take into account the unsteady nature of the air temperatures and release rates, but they are too

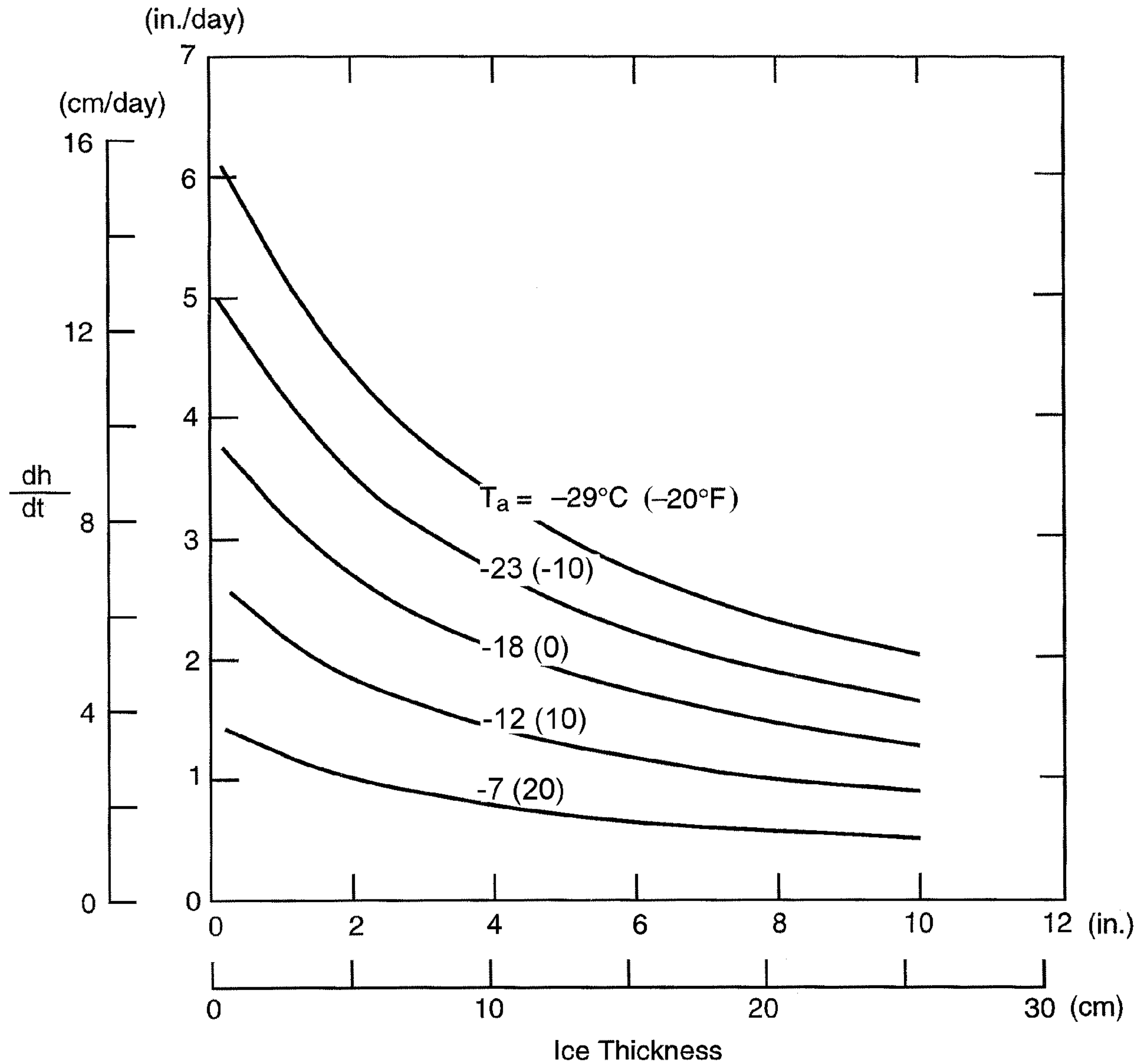



**Figure 3-41. Rate of ice thickening versus ice thickness, for five values of average daily air temperature; $H_{ia}$ = 19.9 W/m$^2$°C (3.5 Btu/hr ft$^2$ °F) is assumed**

detailed for full treatment here. Instead, some steady-state example calculations are presented, as well as some results from unsteady simulations, so as to give an appreciation of whether or not a warm water release causes a significant effect. Occasionally, the effluent from a power plant is diffused uniformly across the receiving river flow, but this is more the exception than the rule. In general this form of release on larger rivers results in insignificant lengths of open water, but a definite suppression of the ice growth (thickness) downstream.

(1) Three example cases are considered: a reservoir discharging 1000 ft$^3$/s (28.3 m$^3$/s) at 36°F (2.2°C) into a river 400 feet wide (122 meters), a reservoir discharging 5000 ft$^3$/s (141.6 m$^3$/s) at 36°F (2.2°C) into a river 500 feet (152 meters) wide, and a very large power plant of nominal capacity of 2400 megawatts discharging 4800 megawatts of waste heat through a diffusing system into a river 2000 feet (610 meters)

wide. As a first approximation, the area of open water, and hence the distance to the upstream edge of the ice cover, can be determined for low air temperatures by estimating the heat transfer coefficient and applying it to the average temperature difference between the water and the air.

(2) Example 1.

(a) *Conditions.*

- Reservoir discharge: 1000 ft$^3$/s (28.3 m$^3$/s) at $T_w$ = 36°F (2.2°C)

- Available heat discharge (in English units):

$$Q = \gamma C_p N (T_w - T_m) = 62.4 \times 1.0 \times 1000 \times 3600 \text{ s/hr} \times (36 - 32)$$

$$Q = 899 \times 10^6 \text{ Btu/hr (or } 263 \times 10^6 \text{ W in SI units)}$$

Open-water area: $A = Q/q_{wa} = \dfrac{Q}{H_{wa}(T_w - T_a)}$

- Width of open water : $W$ = 400 feet (122 meters)

- Length of open water : $L = A/W$

- For $H_{wa}$ = 3.5 Btu/hr ft$^2$°F (19.9 W/m$^2$°C):

| $T_a$ °F (°C) | $T_w - T_a$ °F (°C) | A ft$^2$ (m$^2$) | L ft (m) |
|---|---|---|---|
| 20 (–6.7) | 12 (6.7) | 21.4 × 10$^6$ (19.9 × 10$^5$) | 53,500 (16,300) |
| 10 (–12.2) | 22 (12.2) | 11.7 × 10$^6$ (10.9 × 10$^5$) | 29,200 (8,900) |
| 0 (–17.8) | 32 (17.8) | 8.0 × 10$^6$ (7.4 × 10$^5$) | 20,100 (6,100) |
| –10 (–23.3) | 42 (23.3) | 6.1 × 10$^6$ (5.7 × 10$^5$) | 15,300 (4,700) |

(b) *Discussion.* This reservoir release maintains open water in the river downstream a distance up to 10 miles (16 kilometers) when the weather is mild in winter, and the distance shortens to a little less than 3 miles (5 kilometers) when the weather is very cold (note that for this case –10°F [–23.3°C] is the average daily temperature and not the extreme overnight low). The heat release is equivalent to 240 megawatts, which is about the rate of heat released from a fossil-fueled power plant of nominal capacity of 160 megawatts. The discharge over 2 months adds up to 120,000 acre-ft (1.48 × 10$^8$ m$^3$), and requires a significant reservoir if it is to have that capacity of warm water at the beginning of the ice-covered period.

(3) Example 2.

(a) *Conditions.*

- Reservoir discharge: 5000 ft$^3$/s (141.6 m$^3$/s) at $T_w$ = 36°F (2.2°C)
- Available heat discharge (in English units):

$Q = \gamma C_p\, N\,(T_w - T_m) = 62.4 \times 1.0 \times 5000 \times 3600$ s/hr $\times (36 - 32)$

$Q = 4490 \times 10^6$ Btu/hr (or $1316 \times 10^6$ W in SI units)

- Open-water area: $A = Q/q_{wa} = \dfrac{Q}{H_{wa}(T_w - T_a)}$

- Width of open water: $W$ = 500 feet (152 meters)

- Length of open water: $L = A/W$

- For $H_{wa}$ = 3.5 Btu/hr ft$^2$ °F (19.9 W/m$^2$°C):

| $T_a$ °F (°C) | $T_w - T_a$ °F (°C) | A ft$^2$ (m$^2$) | L ft (m) |
|---|---|---|---|
| 20 (–6.7) | 12 (6.7) | $107 \times 10^6$ ($99.4 \times 10^5$) | 214,000 (65,200) |
| 10 (–12.2) | 22 (12.2) | $58 \times 10^6$ ($53.9 \times 10^5$) | 117,000 (35,700) |
| 0 (–17.8) | 32 (17.8) | $40 \times 10^6$ ($37.2 \times 10^5$) | 80,000 (24,400) |
| –10 (–23.3) | 42 (23.3) | $31 \times 10^6$ ($28.8 \times 10^5$) | 61,000 (18,600) |

(b) *Discussion*. This is a large reservoir release with open water about 11.6 miles (18.7 kilometers) downstream even at –10°F (–23.3°C) air temperature. The heat release is equivalent to 1200 megawatts, which is about the heat released from a fossil-fueled power plant of 800-megawatts capacity. The discharge over 2 months is 600,000 acre-ft ($7.4 \times 10^8$ m$^3$).

(4) Example 3.

(a) *Conditions*. A large power plant of nominal capacity 2400 megawatts is discharging 4800 megawatts through a diffusing system into a river 610 meters (2000 feet) wide. Temperature rise in the river depends on its flow, but under the simplified assumptions used here, the open-water area can be calculated approximately without that knowledge, since it is based on the required water surface area to remove the heat content. This surface area depends on the temperature difference between the water and the air, and the water temperature will be very near 32°F (0°C).

- Available heat discharge:

$$Q = \quad 4800\,MW \times \frac{10^6\,Btu/hr}{0.293\,MW}$$

$Q = 16{,}400 \times 10^6$ Btu/hr

- ! Open-water area: $A = Q/q_{wa} = \dfrac{Q}{H_{wa}(T_q - T_a)}$

- ! Width of open water: $W$ = 2000 feet (610 meters)

- ! Length of open water: $L = A/W$

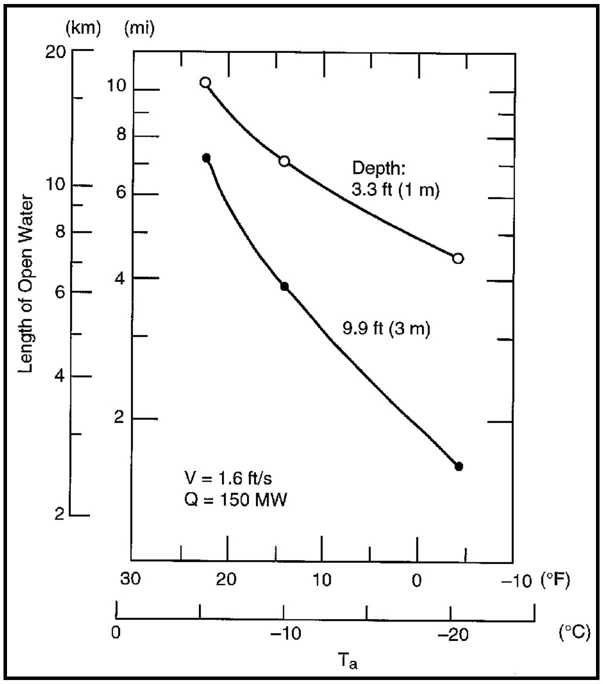
- ! For $H_{wa}$ = 3.5 Btu/hr ft$^2$ °F (19.9 W/m$^2$°C), and $T_w - T_a$ = 32°F (0°C) – $T_a$:

| $T_a$ °F (°C) | $T_w - T_a$ °F (°C) | A ft$^2$ (m$^2$) | L ft (m) | L mi (km) |
|---|---|---|---|---|
| 20 ( –6.7) | 12 (6.7) | 390 × 10$^6$ (362 × 10$^5$) | 195,000 (65,200) | 37 (60) |
| 10 (–12.2) | 22 (12.2) | 213 × 10$^6$ (198 × 10$^5$) | 106,000 (35,700) | 20 (32) |
| 0 (–17.8) | 32 (17.8) | 146 × 10$^6$ (136 × 10$^5$) | 73,000 (24,400) | 14 (23) |
| –10 (–23.3) | 42 (23.3) | 111 × 10$^6$ (103 × 10$^5$) | 56,000 (18,600) | 11 (18) |

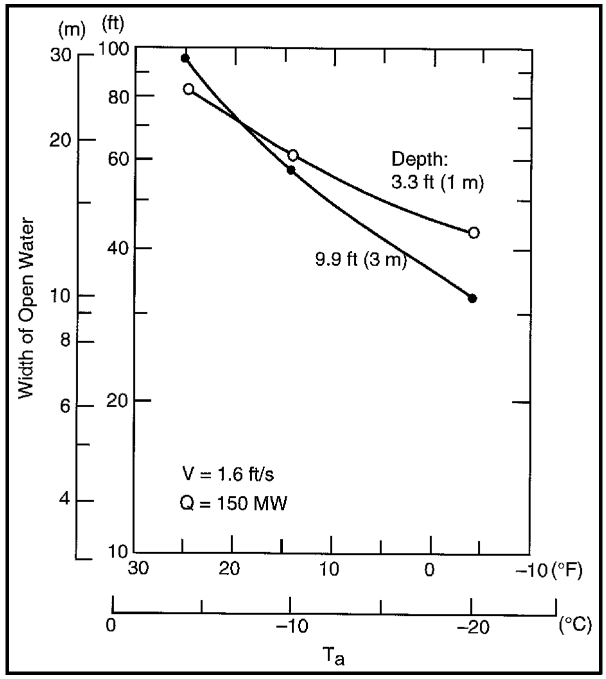
(b) *Discussion*. This is a very large power plant and a very large river. The effect on the ice is open water for many miles or kilometers downstream when the air is mildly cool, but only 16 to 24 kilometers (10 to 15 miles) when the air temperatures are around 0°F (–17.8°C). The simplified assumption, namely that the open-water area is based only on the area required to remove the heat added, is probably not very accurate here, since the complete mixing by the diffuser probably results in water temperatures sufficiently close to freezing that ice will form on top of the slightly warm water if the flow is not too fast. For such a case, a more detailed analysis would be needed. If skim ice forms, however, the warm water still prevents the ice from thickening as much as it would without the addition of heat. Note also that we did not need to know the velocity of the flow or the depth, but merely needed to assume that the flow was fast enough to mix the warm water, and carry it downstream.

*c. Side channel releases.* The most usual method of disposing of a power plant's waste heat to a river is to release it directly at the side of the river. This case is more difficult to analyze because now the rate of transverse mixing of the warm water plume across the river must be considered. As a general rule, the open-water area resulting from a side channel release is quite narrow, on the order of 15 to 30 meters (50 to 100 feet), but very long, on the order of miles or kilometers. While some of the heat is transferred directly to the atmosphere through the open-water area, a significant amount of the heat is transferred to the bottom of the adjacent ice cover and to the bottom of the ice cover downstream of the end of the open water. From the standpoint of maximum decrease of the volume of ice that would be produced in the river without waste heat, this is the most effective use of the waste heat since, once under the ice cover, nearly all of the heat is used to retard ice thickening or to melt it. Simulations are available that enable estimates of the lengths and widths of open water and the amount of ice suppression that results beyond the open water, but they depend on the amount of heat released, the flow velocity, air temperature, depth of the river, and the mixing characteristics of the river. For straight reaches of river, the simulations seem to yield reasonable estimates of open-water extents.

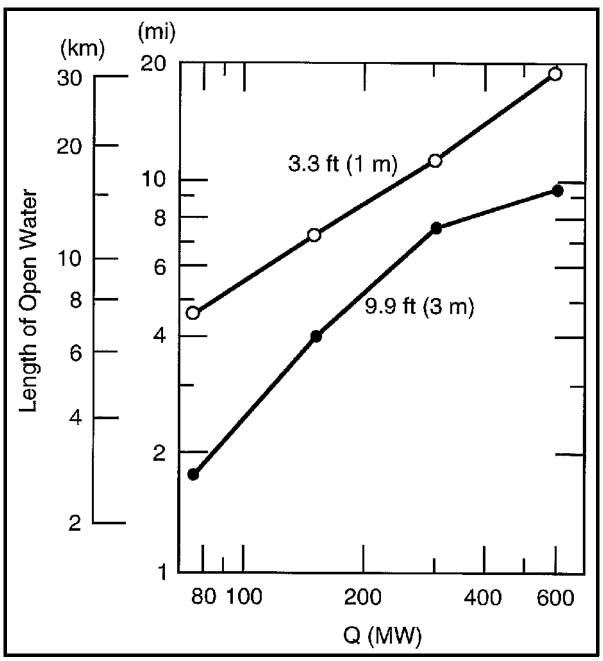
(1) Figure 3-42 shows parametric plots of the lengths and widths of open water that may be expected from a side channel release of warm water into rivers of 1- and 3-meter (3.3- and 9.9-foot) depths, with flow velocities of 0.5 m/s (1.6 ft/s), as functions of air temperature and rates of heat release. These figures are useful for gaining an appreciation of the nature of the ice suppression. Figure 3-42a shows



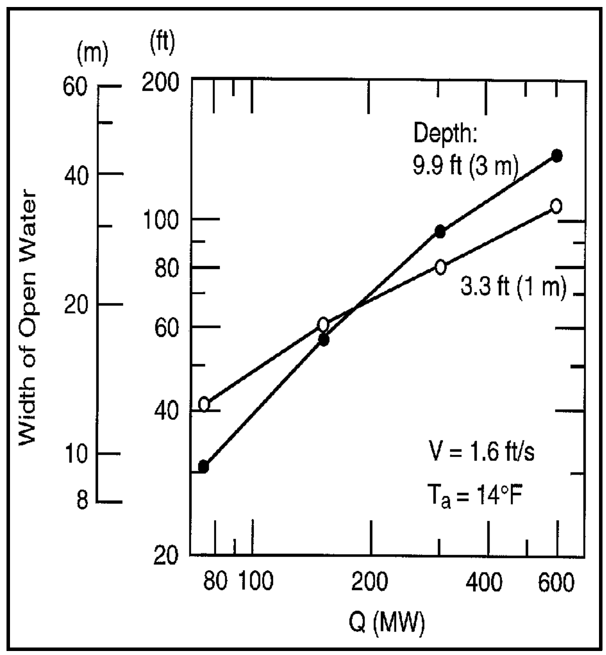

a. Length versus air temperature, heat discharge fixed at 150 megawatts




b. Width versus air temperature, heat discharge fixed at 150 megawatts




c. Length versus heat discharge rate, air temperature fixed at -10 °C (14 °F)




d. Width versus heat discharge rate, air temperature fixed at -10 °C (14 °F)

**Figure 3-42. Length and width of open water resulting from side channel release of warm water into a river of either 1- or 3-meter (3.3- or 9.9-foot) depth, as functions of air temperature and heat discharge rate. In all cases the flow velocity is 0.5 m/s (1.6 ft/s)**

that, as the air gets colder, the length of open water decreases significantly. The length of open water is also much shorter for the deeper river than for the shallower river. Figure 3-42b shows that the width of open water is little affected by the depth, but of course it is narrower at lower air temperatures. Figures 3-42c and 3-42d show the effect of different rates of heat release on the lengths and widths of open water. As expected, both the length and width increase with increasing warm water discharge.

(2) Not apparent from the various plots of Figure 3-42 are the relative amounts of heat from the warm water that are transferred directly to the atmosphere through the open water or that are transferred to the underside of the ice. Less than 30 percent of the heat is transferred through the open water to the air in all cases. This means that 70 percent of the heat is transferred to the ice cover, and either retards thickening or causes thinning of the ice. This effect of the waste heat may extend for many miles or kilometers further downstream, beyond the end of the open-water reach. These effects have been simulated by numerical analysis but are too complex to be described quantitatively here, since the effects vary from site to site. Some general statements can be made, however. The rate of heat transfer to the bottom of the ice cover is more or less proportional to the product of the velocity and the amount by which the water temperature is above freezing. Even temperature differences as small as 0.06°C (0.1°F) have effects that are important, so that any field measurements must use accurate thermometers. The deeper the water is, the further downstream the waste heat will affect the ice. For depths on the order of 1 meter (3 feet), the warm water will have cooled to very near freezing in about 5 kilometers (3 miles), while for depths of about 3.7 meters (12 feet), the effect will extend for as far as 16 kilometers (10 miles).

*d. Mid-channel releases.* Rarely is waste heat from a power plant discharged in the middle of a river. If it were, the effects would be similar to a side channel release and result in a long, narrow open- water stretch. The open water would be wider than a side channel release but shorter because the warm water now mixes and spreads on both sides of the thermal plume, rather than only on one side. There may be cases where it would be desirable from an ice management viewpoint to release an existing source of warm water other than at the side. Before doing this, a simulation of the effects should be made to estimate whether the ice suppression would be effective at the particular site.

## 3-10. References

*a. Required publications.*
None.

*b. Related publications.*

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